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January-February 1937

A REVIEW OF THE PROBLEMS OF THE SUDBURY IRRUPTIVE[1]

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ABSTRACT

The problems of the Sudbury irruptive are approached here mainly from two points of view: (1) the nature of the zone intermediate to the acid and basic portions and (2) the place of these rocks in the general Keweenawan petrographic province of Ontario. It is considered that the nature of the rocks of this intermediate zone does not support the theory of gravitational separation of the basic member but indicates rather the formation of hybrid types at the contact of two separate magmas—one, the more basic, well crystallized; the other, the more acid, still mostly liquid. From an analysis of the now excellent chemical data and a comparison with the allied bodies elsewhere in the province, it is concluded that the basic member represents the product of fractionation of the liquid of the parent diabase magma of this petrographic province and an early separating olivine-diabase component, probably through some filter-pressing action, and that much of the heterogeneity of the rock is primary in the sense that it was brought about by this process of evolution.

INTRODUCTION

Up to the present there have been advanced in all four hypotheses to account for the origin of the internal features of the Sudbury "nickel irruptive" and, though all of these do not find equal favor with Canadian geologists as a whole, their existence indicates at least that the problems are far from being as simple as at first supposed. Why has this multiplication of theories arisen? No doubt the geologist, who regards with suspicion the flights of petrogenetic theory, will reply that the difficulties are all of the petrologist's own making and that the only thing that really matters is that here we

[1] Published with the permission of the Director of the Geological Survey of Canada.

have a sill-like body of igneous rock, acid on one side and basic on the other with material generally of intermediate composition and specific gravity between, the relations one would expect to find in the final product of crystallization-differentiation controlled by gravity. But the difficulty is that this same general relation could be predicated of other igneous occurrences which are not the products of gravitational differentiation of single magma bodies. Recent work in petrology has shown that if there is one point which cannot be treated in a general way it is the nature of the passage from one rock type into another and, be as matter of fact as one likes, that is always a matter for interpretation—interpretation in the light of our knowledge of petrogenesis. It is against this obstacle of interpretation that the narrower view breaks down, for, without lubrication from the theories derived from laboratory and field studies elsewhere, interpretation is a stiff and rusty business.

In the summer of 1930 I had an opportunity of collaborating with Dr. Collins in the mapping of the sheets comprising part of the southern Nickel Range and the area to the south and southwest. Much attention was given to the delimitation of the intermediate zone between the acid and the basic members, and it was possible thus to amplify earlier observations. In what follows an attempt is made to outline the new information and to see how it can best be fitted into the theories of the origin of this body.

As it is unsound geology to separate the study of the Sudbury rocks from that of the others of the same age, a summary is first given of the significant features of this petrographic province.[2]

THE DIABASE—QUARTZ-DIABASE GROUP

General distribution and age.—Dikes and sills of diabase have been described from many localities in the Canadian shield, but it has not been possible in all cases to determine to what period of igneous activity these rocks belong. Thus Cooke[3] has distinguished in the Matachewan district a set of quartz-diabases which are pre-Cobalt

[2] See also T. C. Phemister, "A Comparison of the Keweenawan Sill-Rocks of Sudbury and Cobalt, Ontario," *Roy. Soc. Can.*, 3d ser., Vol. XXII (1928), pp. 121–96.

[3] H. C. Cooke, "Geology and Ore Deposits of Rouyn-Harricanaw Region, Quebec," *Geol. Surv. Can. Mem. 166* (1931), pp. 141–44; "Geology of Matachewan District, Northern Ontario," *Geol. Surv. Can. Mem. 115* (1919), p. 33.

in age. These resemble in many ways the Nipissing diabase which has already been considered to belong to Keweenawan vulcanism, and the only distinguishing feature between the rocks of the two ages seems to be the presence of a much more pronounced alteration of the plagioclase in the older rock. It would thus seem at first sight as though there may have been a possible error in referring all the quartz-diabase sills and dikes of northern Ontario to the Keweenawan. Fortunately, however, the great majority of the diabase intrusions either occur in rocks of late pre-Cambrian age or can be followed through, in intrusions little separated from one another and showing the same structural relations, into adjacent areas where definite evidence of their age can be obtained. In some cases also there have been distinguished in these districts, in addition to the so-called Keweenawan sills and dikes, some older basic intrusive rocks which may possibly be the representatives of Cooke's Matachewan diabases.

Although there are records of the presence of some of these late pre-Cambrian diabases from most of the surveyed parts of the shield, there can be no doubt that their general distribution has been closely related to the basins of latest pre-Cambrian deposition. Thus we can distinguish one great province, set about Lake Superior as its axis, extending on the east to the Ontario-Quebec boundary, on the north to the main line of the Canadian National Railway and on the west to about the Lake of the Woods region. Cooke[4] has already drawn attention to the fact that the Keweenawan igneous activity appears to have died away to the north and east of Lake Opasatika, which is close to the border of Quebec and Ontario. Burwash[5] also has noted in a survey along the eighty-eighth meridian that from Lake Abitibi northward the number of diabase dikes diminishes and the same relation appears to hold generally north of Lake Superior. On the western side of the shield the dikes and sills seem to be absent. A few intrusions which may be referred to this period are found in the Lake of the Woods area, but in the reports dealing with the tract to the north no mention is made of the presence of intrusions

[4] "Geology and Ore Deposits of the Rouyn-Harricanaw Region, Quebec," *loc. cit.*

[5] E. Burwash, "Geology of the Fort Hope Gold Area, District of Kenora (Patricia Portion)," *Ont. Bur. Mines*, Vol. XXXVIII, Part II (1929), p. 44.

which can be classed with this suite. The general boundary of the province then is probably as shown in Figure 1.

Structural relations.—The characteristic forms of the diabase rocks in this Ontarian province then are sills and dikes, the sills appearing most commonly in the stratified rocks while in the more massive formations such as the granites and the Keewatin greenstones the

FIG. 1.—The boundaries of the Ontarian province of quartz-diabase

dikes are the common type. The sills attain a thickness of 1,000 feet, as in the case of the Nipissing diabase at Cobalt, and Collins has estimated that in the North Shore district they may be as much as 2,000 feet. Normally, however, they do not exceed about 100 feet. As to their extent, it is naturally difficult to form any accurate estimate since one must in every case extrapolate from the observed outcrop, but there can be little doubt that in the case of the larger sills, which are well exposed, the area in the plane of their develop-

ment is of the order of 100 square miles, so that these intrusions are to be pictured as very thin laminae inserted between the strata. In a very few instances they have transgressed the bedding as in the case of the Nipissing diabase and some of the Logan sills.

The dikes vary considerably in width, from a few inches to 650 feet. That they cut the sills in by far the greatest number of cases there can be no doubt. This relation has been noted by practically all observers in this region although it is generally assumed that some of the dikes represent the feeders of the sills. In mapping the area south of Sudbury special attention was paid to this point, but in no case was there found evidence of any dikelike feeders to these sills even though the very best of opportunities for their detection were present. The only definite evidence which has been found in the whole region of an actual connection between dikes and sills is that brought forward by Tanton in the Thunder Bay district. There he has traced the rock of dikes continuously into that of the sills in four cases. It is probable, therefore, that in some instances the sills were fed through vertical sheetlike fissures in which the magma finally crystallized as a dike, but the marked absence of the evidence of this connection in the great majority of cases[6] has made the writer consider the possibility of some other mode of supply and he would suggest that these sheetlike bodies moved into their present position through the separation of peripheral offshoots from the parent magma brought about by downwarping about the main irruptive center. This downwarping caused them to move outward into the boundary areas of the province where the shearing-stress component was a minimum. The main center would be beneath the general area of the Lake Superior geosyncline, though the Sudbury district may have been one of secondary magnitude.

Petrographic characters.—One of the most remarkable features of these rocks is their uniformity throughout the whole province. The descriptions given in the various reports are practically identical, the only departure from the monotonous petrographic character being in the case of the larger bodies. There can be no doubt that the prevalent and stable type is a medium- to coarse-grained rock consisting of augite and plagioclase in about equal proportions with

[6] A similar absence of feeders exists in the Paleozoic diabase sills of mid-Sweden.

some titaniferous magnetite and small amounts of interstitial quartz and alkali feldspar. Unfortunately there are but few analyses of this normal type though there are a fair number of the departures from it—a fact which itself is rather indicative of the great uniformity of

TABLE 1

QUARTZ-DIABASES OF ONTARIAN PROVINCE

	1	2	3	4	5	6	7	8	9	10
SiO_2	50.76	50.69	50.80	50.48	49.84	50.12	51.41	48.06	54.46	50.74
TiO_2	1.50	0.53	0.43	.....	.....	0.55	1.20	1.20	0.71	0.88
Al_2O_3	13.90	16.11	19.42	17.03	18.94	15.70	14.13	18.23	14.21	16.41
Fe_2O_3	4.13	0.70	0.97	1.25	1.51	1.42	3.48	−9.57	2.07	1.94
FeO	10.28	7.05	6.67	7.81	6.40	6.89	9.25	.....	6.60	7.62
MnO	0.34	.....	.....	.....	.....	.....	0.30	0.30	0.12	0.29
MgO	4.73	8.20	5.78	9.32	7.39	9.50	5.54	7.80	8.44	7.19
CaO	8.14	12.09	12.68	10.96	10.32	11.30	6.40	11.55	8.84	10.26
Na_2O	2.82	1.78	1.60	1.95	1.99	2.91	3.43	1.87	2.53	2.32
K_2O	0.85	0.78	0.37	0.24	1.28	1.07	1.80	0.27	2.09	0.97
H_2O+	1.57	1.65	0.86	0.82	.....	1.03	1.98	1.98	3.25	1.41
H_2O-	0.23	0.16	0.25	0.22	.....	0.21	0.12	0.12	0.09	0.19
P_2O_5	0.07	.....	.....	.....	.....	.....	0.06	.....	.....	0.07
CO_2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	.....	0.07	.....	.....	.....	0.14	.....	.....	.....	.....
CuO	.....	0.11	0.01	0.04	.....	.....	.....	.....	.....	.....
NiO	0.00	.....	.....	.....	.....	.....	.....	0.06	.....	.....
Total	99.32	99.82	99.84	100.12	100.24	100.48	100.84	99.10	99.83	.....

1. Fine-grained dike of diabase, Rankin Township, Ontario, M. F. Connor, analyst.
2. Quartz-diabase, Silver Bar mine, Cobalt, Ontario, R. E. Hore, analyst.
3. Quartz-diabase, Kerr Lake mine, Cobalt, Ontario, R. E. Hore, analyst.
4. Quartz-diabase, University mine, Cobalt, Ontario, R. E. Hore, analyst.
5. Diabase from Cross Lake, Ontario, analyst?
6. Diabase from O'Brien mine, Cobalt, Ontario, N. L. Bowen, analyst.
7. Coarse-grained quartz-diabase, Wapus Creek, Gowganda, Ontario, M. F. Connor, analyst.
8. Gabbroid and basic phase of quartz-diabase, Cobalt, Ontario, J. O. Handy, analyst.
9. Coarse-grained basic phase of quartz-norite sill, Frechette Township, Ontario, M. F. Connor, analyst.
10. Average of 1–9.

the intrusions since it shows how interest has been focused on what are in effect exceptional occurrences in a province of great petrographic uniformity.

In Table 1 are listed the compositions of what, from the descriptions given, appear to be normal rock in the various bodies studied

up to the present time. (Several analyses have had to be omitted as they are of inferior quality.) The average of these nine is given in column 10 and its norm is: orthoclase 6.12; albite 19.39; anorthite 31.41; diopside 15.17; hypersthene 22.08; magnetite 2.78; ilmenite 1.67; apatite 0.34. That is, it is a rock which contains neither normative quartz nor olivine, which is an interesting point as it indicates

TABLE 2

PURE GRANOPHYRE OF QUARTZ-DIABASES

	1	2	3
SiO_2	76.50	76.41	74.58
TiO_2	.....	.....	tr.
Al_2O_3	12.10	11.94	13.18
Fe_2O_3	1.43	1.49	1.96
FeO	.....	.....	.....
MgO	0.23	0.35	0.24
CaO	1.31	1.32	0.47
Na_2O	4.06	3.79	4.11
K_2O	3.40	3.57	4.52
H_2O+	0.83	0.84	0.79
H_2O-	0.26	0.33	0.36
P_2O_5	.....	.....	.....
FeS_2	.....	.....	.....
CO_2	.....	.....	.....
Fe_7S_8	.....	.....	.....
NiO	.....	.....	.....
MnO	.....	.....	.....
C	.....	.....	.....
Total	100.12	100.04	100.11

1 and 2. Micropegmatitic mesostasis from mottled diabase south of Cobalt, Ontario, T. C. Phemister, analyst.

3. Micrographic intergrowth of quartz and feldspar from Levack district of the Sudbury granophyre, T. C. Phemister, analyst.

that the quartz of these quartz-diabases probably owes its presence to a failure of the early forming orthosilicate to react in the later stages of the crystallization process.[7]

The departures from this normal type we may classify summarily as follows: (1) banding giving adjacent layers of plagioclase- and pyroxene-rich phases, respectively; (2) coarse, pegmatitic patches characterized by more sodic plagioclase, somewhat higher content of quartz and either prismatic augite or hornblende; (3) local accumula-

[7] Phemister, *op. cit.*

tions of granophyre. While we cannot discuss the origin of these here, a word must be said about the granophyres. This material has been formed in two ways: (*a*) by metasomatism and reaction and (*b*) by crystallization-differentiation. The first type occurs always between the quartz-diabase and sediment and is clearly associated with the formation of adinole,[8] while the second appears as irregular mottlings and patches which are confined to no special horizon of the mass.[9] The composition of the latter type is given in Table 2 and for comparison similar material from Sudbury is also listed in column 3.

THE IGNEOUS ROCKS OF THE SUDBURY BASIN AND ALLIED MATERIAL

Of the same general age as the quartz-diabases there are here two igneous masses which in size and textural characters belong rather

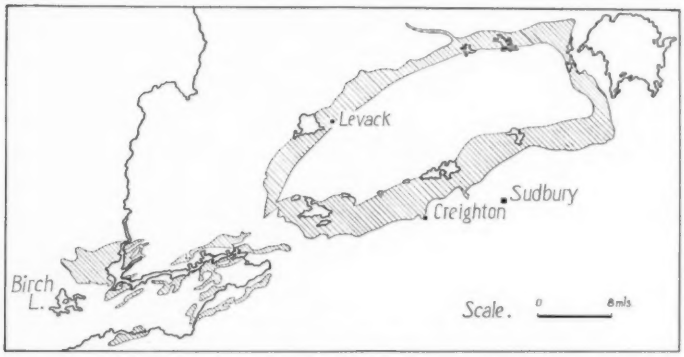

FIG. 2.—Map showing the position of the large mass of gabbro-granophyre to the west of the Sudbury irruptive. Its outlines are shown just north of Birch Lake.

to the plutonic than to the hypabyssal group. These are the Sudbury "nickel irruptive" and a similar mass to the southwest in Shake-

[8] N. L. Bowen, "Diabase and Granophyre of the Gowganda Lake District, Ontario," *Jour. Geol.*, Vol. XVIII (1910), pp. 658–74; A. G. Burrows, "Gowganda Silver Area," *Ont. Dept. Mines*, Vol. XXXV, Part III (1926), p. 15; T. L. Tanton, "Fort William and Port Arthur, and Thunder Cape Map-Areas, Thunder Bay District, Ontario," *Geol. Surv. Can. Mem. 167* (1931), p. 72.

[9] W. H. Collins, "Geology of Gowganda Mining Division," *Geol. Surv. Can. Mem. 33* (1913); R. E. Hore, "Differentiation Products in Quartz-Diabase Masses of the Silver Fields of Nipissing, Ontario," *Econ. Geol.*, Vol. VI (1911), pp. 51–59. Phemister, *op. cit.*

speare and Dunlop townships (Fig. 2). Information is lacking regarding the latter, and though a full description of its characters cannot be given here, we may note one or two significant features before passing on to the rock of the Nickel ranges.

The gabbro-granophyre of Shakespeare and Dunlop townships.— The larger part of this mass is bounded by the Birch Lake granite of Killarnean age. On its eastern border, however, it is in contact with the rocks of the Bruce series of which the main member here is the Mississagi quartzite. The Bruce series is folded, and this deformation has also involved the igneous rocks. The contact of gabbro and sediments is very irregular in plan, but when the flexing of the strata is taken into consideration it is seen that the gabbro is present at this point as two sill-like masses injected prior to the deformation. Within the igneous rock itself there are a few lenses of quartzite. The northern, western, and southern contacts are against the younger granite and are consequently irregular. The general relations suggest that the body as a whole was originally a laccolith or massive sill which digitated into the sediments eastward, and probably westward also, in two or more thinner sills somewhat after the manner of a "cedar-tree" laccolith. It is not possible to estimate closely the thickness of the intrusion but the minimum value for this dimension is 1,000 feet and the maximum 5,000 feet.

The rock all shows evidence of the action of shearing stress, and some parts of it consist of schist or gneiss. In its general characteristics, what we may call the normal rock of the mass is somewhat more acid than the quartz-diabases of the region and would seem to correspond more closely in granularity and composition to the acid phase of the basic member of the Sudbury "nickel irruptive." For our present purpose, however, the most significant feature of the intrusion is the heterogeneity which it shows. Within it are bands of granophyre, of very basic rock, and of material of intermediate composition. Little regularity is to be observed in the occurrence of these different phases, and we find, for example, the most basic modification in contact not with normal rock but with intermediate material, while the granophyre is next to rock of more or less ordinary gabbroic composition.

THE ROCKS OF THE SUDBURY NICKEL RANGES

It is hardly necessary to give here a detailed description of these rocks as all geologists are now familiar with their general nature and the problems to which they give rise. In the following descriptions the granitic part of this great igneous body will be spoken of as the acid and the basic part as the basic member.

The first mapping of the region was carried out by Bell[10] in 1890, and his map shows the presence of the basic member only, which he described as diabase, the rest of the mass not being distinguished from the Laurentian gneiss. His work was followed by that of Coleman[11] in 1893, who first distinguished the micropegmatite from the older gneiss in the western part of the northern nickel range. It was Walker[12] who was the first to recognize that the basic and acid members were part of the one intrusive unit, and he put forward the hypothesis that these two members were derived from a parent magma by gravity-differentiation in situ. As the mapping of the region was continued by Coleman[13] and Barlow,[14] it became clear that the two members could be traced through a continuous elliptical outcrop and a mapping boundary defined between them. In the course of this work the only other suggestion put forward to account for the association of these rocks was that of Coleman, who considered the possibility of the derivation of the acid member through assimilation of the overlying conglomerate by the basic member.

After this earlier work the problem of the relations of the basic and acid members was reopened by Knight,[15] who questioned the existence of a regular decrease in basicity of the mass from the outer

[10] R. Bell, "Report on the Sudbury Mining District," *Geol. Surv. Can.*, Vol. V (1890–91), Report *F*.

[11] A. P. Coleman, "The Rocks of Clear Lake near Sudbury," *Can. Rec. Sci.*, Vol. V (1892–93), pp. 343–46.

[12] T. L. Walker, "Geological and Petrographical Studies of the Sudbury Nickel District (Canada)," *Quart. Jour. Geol. Soc.*, Vol. LIII (1897), pp. 40–66.

[13] A. P. Coleman, "The Sudbury Nickel Region," *Ont. Bur. Mines*, Vol. XIV, Part III (1905); "The Nickel Industry," *Can. Dept. Mines, Mines Branch, No. 170* (1913).

[14] A. E. Barlow, "Report on the Origin, Geological Relations and Composition of the Nickel and Copper Deposits of the Sudbury Mining District, Ontario, Canada," *Geol. Surv. Can.*, Vol. XIV (1904), Part *II*.

[15] C. W. Knight, *Roy. Ont. Nickel Comm.* (1917), pp. 115–21; "The Chemical Composition of the Norite-Micropegmatite, Sudbury, Ontario, Canada," *Econ. Geol.*, Vol. XVIII (1923), pp. 592–94.

to the inner margin. This matter was also taken up by Phemister,[16] who studied the mineralogical variations across the intrusion at many parts of its outcrop. From the results of these traverses it was concluded that there was no regular composition gradient and that the break between the basic and acid members was too sharp to be explained by gravity-differentiation alone. It was suggested that a better explanation of the relations might be obtained by entertaining the hypothesis that two consanguine intrusions were present, the basic member being the earlier and the acid the later, and that the interval between the two injections was comparatively short, so that opportunities were given for the formation of a hybrid rock at their contact. Within the basic member itself some gravitative differentiation and movement of the late-forming acid liquid was considered to have taken place with the production of a variety of gabbro richer in micropegmatitic mesostasis toward the top of the intrusion and a more basic part about one-half the thickness of the sheet from its base. Walker[17] later made a detailed chemical study of the variations across the outcrop of the rocks at different points and has given a magnificent series of analyses which he claims supports his original theory that these rocks have originated through gravity-differentiation in situ.

Since these studies have been so intensive, it seems hardly necessary to cover their scope again in the present work. We have now in them full information regarding the nature of (*a*) the mineralogical and (*b*) the chemical variations across this mass, and so far as this type of evidence is concerned, it is a matter for analysis and interpretation. There do remain, however, two points which could be dealt with to greater advantage in the more detailed mapping of the area, namely, (*a*) the precise nature of the zone between the basic and the acid members and its thickness and (*b*) the relation of these rocks to the other intrusions of the same age in Ontario. The evidence regarding these two matters will be dealt with mainly in the following descriptions and the problems involved in the petrogenesis considered later.

[16] T. C. Phemister, "Igneous Rocks of Sudbury and Their Relation to the Ore Deposits," *Ont. Dept. Mines*, Vol. XXXIV, Part VIII (1925).

[17] A. P. Coleman, E. S. Moore, and T. L. Walker, "The Sudbury Nickel Intrusive," *Univ. Toronto Studies*, Geol. Ser., No. 28 (1929).

As the brief summary given above shows, it was found possible in the mapping of this area to define the boundary between the acid and the basic members. That is, then, it must always be recognized that, whatever more detailed studies may show regarding similarities between these rocks, any geologist confronted with the problem of the mapping of the area would have no difficulty on the whole in separating the one rock from the other. It is necessary to emphasize this here because, on the one hand, the focusing of attention on the lower part of the mass close to which the sulphide ores occur, and its having been named norite, and, on the other hand, the insistence on a continuous composition gradient from top to bottom of the intrusion have tended to divert attention from this most fundamental relation. True norite, if it is present at all in the intrusion, exists only as a modification of the basic member, which is on the whole a much more acid rock than true norite, and, whatever be the relations of the chemical compositions of the upper parts of the basic member and the lower parts of the acid member, they are quite distinct in the field. This was made abundantly clear to the writer, especially during the last field season. The mapping of the district had involved the study of the diabases described in the previous section, and, though within these many variations occur, no difficulty was encountered in establishing the general type and recognizing it wherever met. When the mapping came to include the nickel irruptive, it was precisely the same type of relation which was found to obtain in the basic member. The variations were all within one definite rock type which could always be recognized.

Having emphasized this point, we can proceed to the next field observation, that between the basic and the acid member there is a zone of material which cannot be referred with certainty in the field to either of these rocks. The width of this zone is variable and the variation is somewhat irregular. The greatest width observed was 286 yards, and all widths down to practically zero occur. Since this zone is critical in any explanation of the relations of the acid and basic members, considerable attention was paid to the mapping of it and to its petrography. A description of this material is given in succeeding paragraphs, but before proceeding to it, it seems best to give first an outline of the characters and variations of the two mem-

bers so that comparisons can be made with them.[18] Such a summary description is best given by an account of a traverse made across these rocks in the neighborhood of the boundary of Snider and Creighton townships from the base of the basic member into typical micropegmatite.

The rock in contact with the basic member in this locality is the large intrusion of younger granite stretching from Copper Cliff to O'Donnell. It has markedly metamorphosed the basic member, and immediately to the east there is a zone of material which in mapping had to be classed as an injection complex of granite-gneiss and gabbro. In the granite near to the basic member there are many large slabs of metamorphosed basic rock, and some of these are clearly altered representatives of the basic member.

The unmetamorphosed rock closest to the granite is medium-grained and shows distinct traces of diabasic texture. One of its most noticeable characteristics is the abundance of grains of azure-blue quartz which it contains. These grains are evenly distributed through the rock and are quite unconnected with the underlying granite. The relative abundance of this quartz is characteristic for the lower part of the basic member throughout all but the most westerly part of the southern Nickel Range and its presence is a great aid in distinguishing between the basic member and the various other basic rocks with which it is in contact. In places the texture becomes somewhat coarser than usual, and where this is the case, the amount of blue quartz increases markedly, giving what appears in the field to be rather dark granite. The other constituents of the rock are plagioclase, pyroxene and amphibole, and biotite.

This is the material encountered for the first $\frac{3}{8}$ mile of the traverse. At this distance the blue quartz has begun to disappear and the rock assumes a more basic appearance. This dark rock is distinctly coarse-grained and consists of feldspar laths about 2–4 millimeters long and 0.75 to 1.5 millimeters broad, with more equidimensional crystals of a ferro-magnesian mineral. Some biotite is also present, but it does not appear to be as abundant as in the material

[18] For a full description of the mineralogy of these rocks and for reference to earlier work see T. C. Phemister, "A Comparison of the Keweenawan Sill-Rocks of Sudbury and Cobalt, Ontario," *Roy. Soc. Can.*, 3d ser., Vol. XXII, Sec. IV (1928), pp. 170–87.

closer to the base. The plagioclase is almost black, with resplendent luster, and the laths show a rough parallelism which gives the rock a directed character. Material of this general nature continues to be met for the next $\frac{3}{8}$ mile where the rock takes on a somewhat different appearance. In addition to the dark, well-formed plagioclase crystals, there appears also a white to greenish-white feldspathic substance between the plagioclase grains. The diabasic texture is more frequent than in the more basic lower material. Here also the partly directed character is absent, the plagioclase crystals no longer showing any rough parallelism. This change continues in the rock to the north, giving material essentially similar to the somewhat more basic phases of the diabases of the region. This variety of the basic member is found for the next $\frac{3}{8}$ mile, but within this distance the rock becomes distinctly less basic in appearance and at the end of the interval it is similar to the coarser-grained phases of the diabases. From this phase there is a rapid passage into material which is distinct from the rock to the south but which is not micropegmatite. This is the zone of intermediate rock already referred to, which is at this point 100 yards across. On the other side of the zone typical granophyre is met.

The micropegmatite is a pink rock containing patches of dark mineral and grains of quartz. Although microscopic examination shows this pink material to be a micropegmatitic intergrowth of quartz and alkali feldspar, in hand specimen it has all the appearances of orthoclase, showing good carlsbad twinning and continuous cleavage surfaces. The amount of visible quartz varies, as does also the proportion of dark mineral; but, on the whole, there seems to be little regular variation within the rock, though as the northern contact is approached the proportion of dark mineral increases somewhat.

Microscopic petrography.—The lower part of the basic member consists of plagioclase, amphibole, pyroxene, biotite, and quartz. The plagioclase is markedly zoned on its periphery, though the inner part is homogeneous. This inner part contains abundant minute inclusions which give the mineral a brown appearance in thin section quite distinct from the more glassy character of the peripheral layers. Its composition is about $ab_{50}an_{50}$, but it is difficult

to say what the gross composition of the whole crystal is since one cannot estimate the amount of the components in the zoned outer layer. It must, however, be somewhere in the calcic part of the andesine division. The amphibole present is of three types: (1) aggregates of very short prisms which are clearly pseudomorphous after monoclinic pyroxene of which a few fragments still remain; (2) separate crystals possibly of a primary nature; and (3) definitely primary green hornblende. The pyroxene after which the amphibole is pseudomorphous shows a partly interstitial relation to the plagioclase and this relation is preserved in the pseudomorph. In places it exhibits also the tendency, seen so frequently in the coarser phases of the diabases, to develop into long prismatic individuals which are sometimes euhedral toward the plagioclase. The second variety of amphibole shows blue-green to yellow-green pleochroism and forms somewhat prismatic crystals of irregular outline. It is impossible to say whether or not it has formed after some other mineral, for no sign of any primary constituent appears within it.

Brown biotite is abundant and is present both as larger plates and as smaller flakes which are intimately associated with the blue-green amphibole. The quartz is present as interstitial material and appears to have replaced the plagioclase on its boundaries, forming a pseudo-micrographic intergrowth similar to that described by the writer[19] from the Nipissing diabase. It occurs also as larger plates in which are set the plagioclase crystals. It seems to be contemporaneous in formation with much of the blue-green amphibole and biotite.

The alteration of the pyroxene to amphibole in this rock cannot be ascribed to weathering, for care was taken to ensure that the sections were cut from quite fresh material. Dynamic metamorphism also can hardly be the cause since the alteration appears in rocks in which there are no signs of the operation of shearing stress in the other minerals and it is probably therefore to be referred to reaction processes occurring in the later stages of the consolidation of the rock.

In the overlying more basic facies the most abundant mineral is

[19] "A Comparison of the Keweenawan Sill-Rocks of Sudbury and Cobalt, Ontario," *op. cit.*, pp. 170–87.

dusty-brown plagioclase, the composition of which is about $ab_{45}an_{55}$. Two types of pyroxene appear: (1) monoclinic, similar to that in the rock beneath; (2) euhedral varieties forming short prisms with small prism faces. The latter type is mostly hypersthene, but some of the crystals consist of an intergrowth similar to that already described by the writer[20] of monoclinic and orthorhombic material. In all the sections studied, unfortunately the pyroxenes are considerably altered to pale fibrous amphibole.

A little quartz occurs here also and is situated in the angles between the plagioclase crystals which it embays slightly. The only other mineral of any importance is biotite, which occurs in much smaller amounts than in the rock nearer the base.

Toward the top of this more basic layer significant changes appear in the mineralogy and texture of the rock. In the first place, the quartz increases slightly in amount and replaces the plagioclase to a much greater extent than formerly, producing pseudo-micrographic intergrowths. The orthorhombic and allied pyroxene diminishes also, and the only pyroxene present is the monoclinic variety, which in some cases shows a partly ophitic relation to the plagioclase while elsewhere it develops the prismatic character already noted. It gives place on its boundaries to green hornblende and is usually altered within to bladed and fibrous amphibole crystals which belong to the tremolite-actinolite group.

In the upper part of the basic member the most abundant mineral is still plagioclase, but it has decreased somewhat in amount while the quartz has increased. It is much zoned, but the inner part usually preserves some of the brown color of the feldspar of the rest of the rock. The boundaries against the quartz are very ragged and irregular; pseudo-micrographic intergrowths with the quartz appear and in some cases the latter mineral forms veins in the plagioclase. As well as the quartz there is present also, as an essential constituent, a true micrographic intergrowth of quartz and alkali feldspar. The feldspar in this intergrowth is of the microperthite type in which the grain size of the individual components varies considerably. The ferromagnesian minerals are the same as those described for the ma-

[20] *Ibid.*, pp. 176–79.

terial beneath, the amphibole here clearly replacing monoclinic pyroxene which shows a partly ophitic relation to the plagioclase.

In the granophyre the main constituent is a micropegmatitic intergrowth of quartz and feldspar, but there are almost invariably present a few crystals of very acid plagioclase, varying in composition from oligoclase to albite. The micropegmatitic intergrowths radiate in roughly triangular sectors from the acid plagioclase crystals. The feldspar of the intergrowth belongs to the potash-soda division and contains only a very small amount of anorthite, 3 per cent.[21]

Epidote is the most important ferromagnesian mineral present and occurs in clusters of large crystals and also in separate grains. With it is sometimes associated a very finely shredded biotite and blue-green hornblende. Close to the basic member it contains also some apatite and occasionally a little primary calcite.

This summary description will show the general nature of the rocks up to and beyond the zone of intermediate material, which will now be dealt with in some detail.

THE INTERMEDIATE MATERIAL

Structural features of the rock at this point.—The width of this zone and its position in the irruptive for the area mapped in 1930 are shown in Figure 3, and this presents the relations for the broadest section of the mass. As this zone is approached one finds that the rocks show signs of having been acted on by deforming forces. Some of the material shows a directed structure and at points distinct foliation appears, mica being the most abundant dark mineral. The intensity and extent of this deformation increases westward, so that south of Fairbank Lake practically all the rocks of the intrusion are affected and precise delimitation of the primary rock types becomes extremely difficult.

In this vicinity also there are included slabs of quartzite, and though these cannot be described as abundant, their presence here is of interest as none was met in the main part of the basic member. Into this horizon also there have been injected thin granite dikes which seem to be more abundant here than elsewhere in the mass.

[21] *Ibid.*, p. 182.

This granite is quite undeformed, and as it has exerted no metamorphic influence on the adjacent rock it is disregarded in what follows.

An interesting feature of the relations is that south of the intermediate zone there occurs a band of very coarse, pegmatitic gabbro similar to the coarse material already described as a common facies of the quartz-diabases. This zone widens considerably westward and in the vicinity of Vermilion River occupies about a third of the total outcrop of the basic member.

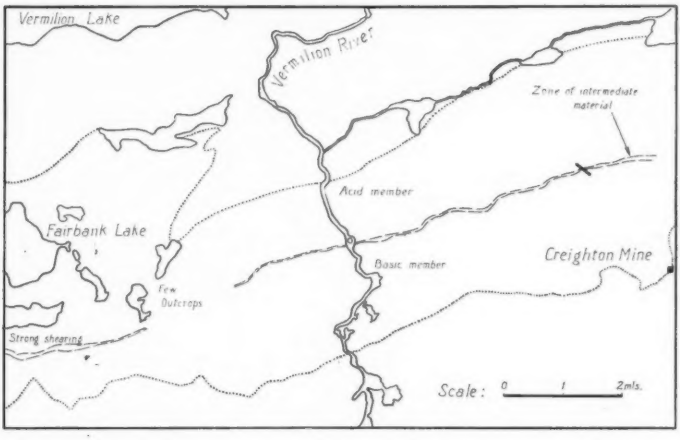

FIG. 3.—Map of the zone of intermediate material in the southwestern part of the irruptive.

Petrography of the intermediate material.—In the preceding section the nature of the upper part of the basic layer was described, and it was compared to the coarser and more acid phases of the diabases of the province. Many traverses were made from this rock into typical micropegmatite, and a general summary will now be given of the nature of the rocks between the two principal members.

It was early noted in these traverses that the rock within the zone of intermediate material did not vary in a uniform manner. In some traverses it was found, for example, that bands of rock, quite definitely of the basic member, appeared within the zone, and in some

cases also, after one had left this zone in going south in the traverse and the rocks were typically of the basic member, one would come upon an isolated outcrop of the material of the intermediate zone. Such material was found in one case 135 yards within the basic member. Further, there is within the zone material which quite definitely belongs to the micropegmatite but which is separated from it by intermediate rock. These relations suggest that we are not dealing simply with a regular transitional band between the acid phase of the basic member and the typical micropegmatite in which there is a gradual increase in the acid components of the rock, but rather that we have here a somewhat heterogeneous mixture of the three types—basic member, micropegmatite, and intermediate rock.

The various phases of the rock will be described first, and this will be followed by an account of their relations within the transition zone.

Most basic variety (*A*).—In hand specimen this resembles the acid part of the basic member. The feldspar is white, usually with a pinkish cast, and, especially on weathered surfaces, it can be seen to have a partly poikilitic relation to the dark minerals. It differs from the basic member, however, in being finer grained, in being of somewhat less uniform texture, and in the presence of occasional grains of quartz. The dark mineral present is no longer mainly hornblende but hornblende with biotite, and as the biotite crystals sometimes form short lenslike patches, the rock shows a slightly gneissose structure.

Microscopic examination shows some significant departures from the more acid layer of the basic member. These are:

1. The plagioclase exhibits a tendency to form crystals which are somewhat more prismatic and also smaller than in the basic member. The composition of the mineral is still calcic and the brownish tint remains, though it is paler than in the typical material, but zoning is very pronounced and on the crystal boundaries considerable replacement by quartz has taken place. Alteration also is widespread, the secondary material being epidote granules with which are usually associated white mica flakes.

2. Quartz and microperthite as a micropegmatitic intergrowth are more abundant here. This material in places tends to radiate from

the zoned plagioclase crystals, the outermost zone of the latter being continuous with the feldspar of the intergrowth. Some of the quartz also occurs separately as mosaics of grains.

3. The only amphibole present is the blue-green to yellow-brown variety. Larger crystals are present, and it is they that form the partly poikilitic growth with the feldspar. They usually contain much quartz and on their boundaries pass in many cases into irregular intergrowths with the same mineral. As well as forming these larger crystals, however, this amphibole occurs also as aggregates of smaller grains which are intergrown very irregularly with quartz, biotite, epidote, apatite, and titanite. In these intergrowths only the apatite shows universally its own crystal boundaries. In a few cases these intergrowths project into the plagioclase crystals as though replacing them.

4. Epidote is an important constituent of the rock. As already mentioned, it occurs as an alteration product of plagioclase and also as a component of the hornblende-biotite intergrowth. In addition to these occurrences it is present also in large aggregates of about the same size as the plagioclase crystals. These aggregates are quite unconnected with any veins and seem to be integral with the rest of the rock.

5. Titanite appears here in considerable amounts and forms most commonly spherules with a grain of ilmenite at their centers. These spherules occur usually in the hornblende-biotite aggregates, but sometimes appear within the other minerals of the rock.

This rock does not correspond to any ordinary type. In Johannsen's classification it would lie between granogabbro and basic granodiorite but its textural characters do not agree with either of these types. In Figure 4*A* a camera-lucida drawing is given which shows some of the significant features of the rock. This field, unfortunately, does not show the titanite spherules.

In Table 3 the composition and the norm of this variety are given in columns 1 and 1*a*, respectively. The relatively basic character of the normative plagioclase should be noted, though it is to be remembered in this connection that some of the lime combined with alumina appears in the rock as apparently primary epidote. The content of TiO_2 and P_2O_5 is exceptionally high for these rocks

and, as thin sections show, seems to be characteristic for this horizon of the mass.

Hybrid rock (*B*).—In hand specimen this differs from *A* in the decidedly pink color of its feldspar, the complete absence of any sign of diabasic texture and in the markedly prismatic character of some of its feldspar crystals. The texture is not uniform, there being streaks and patches richer in the lighter-colored constituents.

TABLE 3

ROCKS OF THE INTERMEDIATE ZONE

	1	2	3		1a	2a	3a
SiO_2	54.87	62.24	62.35	Quartz	17.70	21.12	24.66
TiO_2	2.56	1.80	1.45	Orthoclase	6.67	7.23	11.68
Al_2O_3	12.59	12.07	11.79	Albite	16.77	37.20	28.82
Fe_2O_3	3.43	4.22	3.44	Anorthite	22.24	9.73	11.12
FeO	8.47	6.32	7.01	Diopside	11.28	7.18	0.71
MgO	3.29	1.63	1.29	Hypersthene	11.18	5.67	10.36
CaO	9.27	4.81	4.53	Magnetite	4.87	6.03	4.87
Na_2O	2.02	4.40	3.43	Ilmenite	4.86	3.50	2.89
K_2O	1.09	1.23	2.01	Apatite	3.70	2.02	3.70
H_2O+	1.16	0.84	0.64				
H_2O-	0.20	0.25	0.26				
P_2O_5	1.51	0.81	1.59				
CO_2	None	Trace	Trace				
Total	100.46	100.62	99.79				
S.G.	2.86	2.82	2.83				

1. Rock of the intermediate zone between the acid and the basic members, north of Creighton, Sudbury; (*A*) of text: T. C. Phemister, analyst.

2. Rock of the intermediate zone between the acid and the basic members, north of Creighton, Sudbury; (*B*) of text: T. C. Phemister, analyst.

3. Rock of the intermediate zone between the acid and the basic members, north of Creighton, Sudbury; (*C*) of text: T. C. Phemister, analyst.

Microscopic examination shows that the feldspar here is no longer similar to that of the basic member but has become more sodic, about $ab_{85-70}an_{15-30}$. It is much altered to white mica and epidote and its pink color is due to the presence of dusty iron oxide. The outer part of many of these plagioclase crystals consists of coarse microperthite and this material is continuous with the feldspar of the micrographic intergrowth of quartz and feldspar. The amount of the latter is greater than in *A*, being as much as 30 per cent in some cases, though usually much less. Along with this increase in

micropegmatitic material, however, there does not go a corresponding decrease in dark minerals, so that we find varieties which contain not only more micropegmatite but also more hornblende and biotite than *A*. The amount of dark mineral, however, varies considerably from point to point so that no generalization can be made regarding the relations of these two components.

The amphibole is of the blue-green to yellow-brown type and in no case is it pseudomorphous after any earlier-forming constituent. It occurs typically as irregular intergrowths with biotite, quartz, titanite, and ilmenite and sometimes forms clusters of grains, sometimes unconnected, streaked masses, and sometimes isolated crystals. It juts into the plagioclase and at many points clearly replaces that mineral.

The amount of titanite is even greater in this rock than in *A* and, as in the latter, it is always associated with ilmenite which occurs as a nucleus of round grains. Epidote is an abundant constituent here also and apatite is present in considerable quantities, usually associated with the amphibole as large euhedral crystals.

This rock, like *A*, does not correspond to any standard type. Its textural characters indicate some abnormal process in its formation, so that, although mineralogically it would fall into the group of the basic granodiorites, this name is hardly justified. Its general characters are shown in Figure 4*B*.

In Table 3 the composition and norm are given in columns 2 and 2*a*, respectively. Most noteworthy is the extremely high content of soda, much in excess of the ordinary amount met with in these rocks and in marked contrast to the type *A* of column 1. Though still present in considerable proportions, the P_2O_5 and the TiO_2 are not so abundant as in the latter rock.

Most acid variety (*C*).—This rock is characterized by an abundance of markedly pink feldspar crystals between which run lenses and patches of biotite. The feldspar shows glassy cleavage planes and carlsbad twinning is frequently present. Some of the crystals are long and in places the rock becomes very coarse grained. Here the biotite aggregates occur in long sinuous streaks between the large feldspar crystals, giving a somewhat gneissose texture. Grains of quartz are scattered throughout the rock.

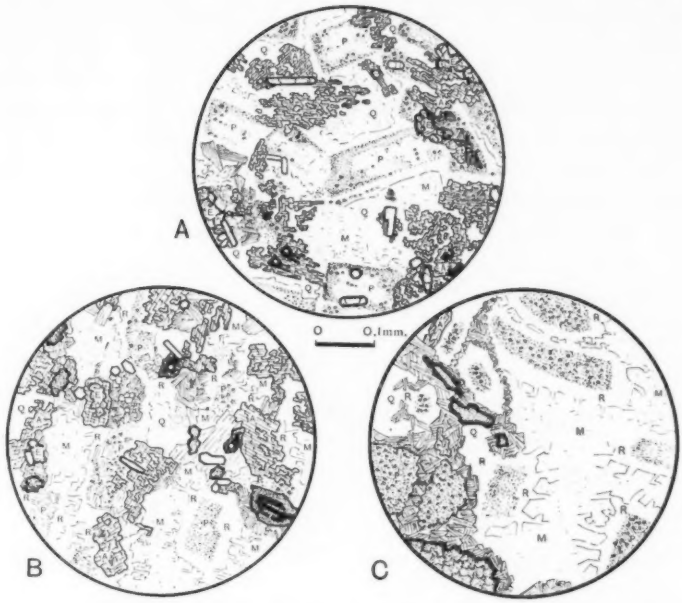

FIG. 4.—Rocks from the zone between the basic and acid members. *P*, plagioclase; *A*, amphibole; *Q*, quartz; *M*, micropegmatite; *R*, microperthite; *E*, epidote. The clear, sharply defined crystals of high relief are apatite. The highly pitted and refracting mineral is titanite. The shredded mineral is biotite.

A. Most basic variety. Note alteration of the calcic plagioclase and its passage into more acid material on its boundaries. This mineral is also replaced by biotite, blue-green to yellow-brown amphibole and epidote. Note, also, how the hornblende frequently shows an irregular intergrowth with quartz. In the upper, right-hand corner is an aggregate of epidote crystals. Apatite is very abundant.

B. Hybrid rock. Note the extremely irregular texture due to the relations of the dark minerals to one another and to the plagioclase. Also note the abundance of apatite and the development of titanite, here chiefly about the iron ore.

C. Most acid variety. The calcic plagioclase crystals are much altered to epidote and some white mica. They pass abruptly into microperthite on their borders, and the latter is continuous with the feldspar of the micropegmatite. Note the breaking across of the plagioclase crystals by biotite. More acid plagioclase crystals are present, and these show alteration mainly to white mica with but small amounts of epidote. They are really more abundant than shown in this field. On their outer parts they pass into microperthite. Note the remarkable development of titanite.

The amount of dark mineral varies considerably but on the whole there is less than in *B*. The rock is distinctly more basic in appearance than the micropegmatite proper which, however, it resembles in hand specimen in the abundance of pink feldspar.

In thin sections of the rock it is seen that the feldspar, though it shows usually carlsbad twinning, occasionally shows albite and pericline as well. It is very sodic plagioclase and all of the crystals do not appear to be of the same composition. The most calcic are $ab_{70}an_{30}$, but the commonest type is $ab_{95}an_{5}$. On the outer part the crystals consist almost invariably of microperthite and some consist mainly of this material. The inner parts of the crystals are always much altered to white mica and epidote.

The dark mineral present is mainly biotite in small flaky crystals which form aggregates in which there is also present a great deal of titanite and some epidote. The hornblende of *A* is still present here but in much smaller amounts. These aggregates of darker minerals occur usually as narrow bands and impart a directed character to the rock.

The amount of micropegmatite is variable, in some cases being less than in *B*, in others more. In all cases the feldspar of the intergrowth is microperthite. Apatite prisms are present here but are somewhat less abundant than in *A* and *B*.

As well as the acid plagioclase there occur also patches of epidote and white mica aggregates which represent apparently crystals of more calcic plagioclase. Some of these are shown in Figure 4*C*. This material is frequently surrounded and veined by biotite.

Just as with *A* and *B*, this rock does not correspond to any ordinary type. It is much too basic for a granite, the proportion of dark mineral present being about that found in a diorite, while, on the other hand, the high content of alkalic feldspar and quartz exclude it from the latter group. It approximates most closely to a granodiorite but texturally departs radically from that type. The general relations are shown in the camera-lucida drawing of Figure 4*C*.

In Table 3 are given the composition and norm. As these show, the rock closely resembles the type *B* in the ratio of silica and bases but differs from it in the smaller amount of Na_2O. It departs also from both *A* and *B* in the increase in the amount of K_2O present,

the ratio of the alkalis approaching more closely that of the typical granophyre. The P_2O_5 percentage is very high though the TiO_2 content is lower than in *A* or *B*.

Distribution of these varieties in the intermediate zone.—Having outlined the varieties of rock found in the zone of intermediate material, we can now complete the description of the latter by giving an account of the relations of these varieties to one another within the zone. This can be done shortly by means of a diagram of a typical traverse which is given in Figure 5. This figure shows that it is by no means a case of passing gradually from more basic to less basic material, but that we have rather an irregular banding of rock varying considerably in composition and texture. Thus the most acid material is not adjacent to the micropegmatite and the

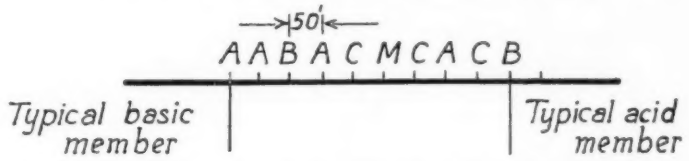

FIG. 5.—A cross section of the intermediate zone showing the distribution of the rocks of Figure 4. *M* signifies the normal acid member.

most basic phase occurs on the side of the zone remote from the basic member as well as being next to the latter. The same general relations were met in all of the traverses. The irregular heterogeneity of the material of the zone made it practically useless to endeavor to map by tracing changes in the rock, and the method used was to continue in the line of the traverse until either the typical basic member or the acid member was reached. The band given in the map (Fig. 3) should therefore be considered as defining the maximum width of the transitional material.

As already mentioned, within the basic member occasional isolated outcrops were encountered of material of the intermediate zone. This material consists of *B* and must be regarded as a short, irregular band somehow or other totally enclosed in the basic member

Collins[22] claims that in the Levack and Maclennan sections the

[22] W. H. Collins, "Life-History of the Sudbury Nickel Irruptive, I. Petrogenesis," *Roy. Soc. Can.* 3d ser., Vol. XXVIII, Sec. IV (1934), pp. 123–77.

passage from basic to acid member is gradual and regular as shown by the curves he has drawn. But, in the first place, it should be noted that, as can be seen from a study of Figure 4, it is possible for three specimens taken in this zone to show such a regular change for most of the oxides. It would depend on the location of the specimens, and one might well miss in this way the significant breaks and reversals in the change from the one member to the other. In the second place, the curves themselves do not show the progressive change claimed for them. This is manifest in the case of Al_2O_3 and Fe_2O_3. The amounts of these two oxides have been added but this makes the case no better (one cannot see why these two oxides should be added as presumably most of the one would be in the feldspar molecule, the other in magnetite, etc.). One of the most significant oxides is Na_2O, and it has obviously been impossible to draw any straight line for it since in the Maclennan traverse the highest amount shown is in a rock of the intermediate zone itself. Until, therefore, a further and more detailed description is given of the zone in these two sections, I am not prepared to accept the evidence as indicating an essential departure from the relations described above.

THE EXPLANATION OF THESE RELATIONS

The hypotheses advanced from time to time to explain the relations of the acid and basic members of the Sudbury igneous mass may be grouped as follows:

1. The acid member was produced from the magma of the basic member by assimilation of overlying sedimentary rocks.

2. All the rocks were derived from a magma homogeneous at the time of intrusion.

3. The parent magma as intruded was heterogeneous.

4. Two separate and distinct magmas were injected, one corresponding to the basic and one to the acid member.

We shall consider these hypotheses in the order given, but before doing so it is necessary to develop a satisfactory interpretation of the relations within the intermediate zone. The form of the mass and its structure have already been discussed elsewhere.[23]

[23] See Phemister, "Igneous Rocks of Sudbury and Their Relation to the Ore Deposits," *op. cit.*, pp. 23–24.

INTERPRETATION OF THE INTERMEDIATE ZONE

The characters of this zone have been described, and this description must have made it evident that a full explanation of the relations must elucidate these three classes of phenomena: (*a*) the chemical relations, (*b*) the peculiar mineralogy and texture of the rocks of the zone, and (*c*) the mode of their occurrence within this band. We shall start with a discussion of the first of these.

a) *Chemical variation.*—In Figure 6 are plotted at *b*, *c*, and *d* the compositions of the rocks *A*, *B*, and *C* of the intermediate zone, and at *a* and *e* are given the compositions of the upper part of the basic member and lower part of the acid member, respectively, as given by Walker. These curves show clearly that the rocks of this zone are certainly not simple mixtures of the adjacent acid and basic members and their departures from such simple mixtures are: (1) poverty of Al_2O_3; (2) richness in Fe_2O_3+FeO; (3) richness in CaO; (4) poverty of MgO; (5) extreme richness in Na_2O; (6) poverty of K_2O; (7) richness in TiO_2; and (8) richness in P_2O_5. If they have been derived from the basic member, the latter must have undergone some form of metasomatism, but what the precise nature of this change was we can determine only by assuming that some constituent was unaffected during the change. Thus, if MgO remained constant, the percentage composition of the material added and subtracted in producing the rock *b* of the variation diagram is given by the intersections of the appropriate lines for Al_2O_3, etc., with the ordinate through $SiO_2 = 69$ per cent. It is very doubtful, however, if such an assumption is justified, for the textural evidence indicates that the substance of both amphibole and biotite has been able to diffuse some distance through the rock.

The curves of the variation diagram are those which Harker has already suggested to be characteristic of hybrid rocks, and the only hypothesis which gives a satisfactory explanation of the relations is that the rocks have been produced by reactions between materials of the acid and basic members—reactions in which considerable diffusion of substance was possible. One of the most significant features of the process is the great increase in the $Na_2O:K_2O$ ratio in the final product. It seems most probable that this increase is to be referred to some form of soda transfer from the magma of the acid

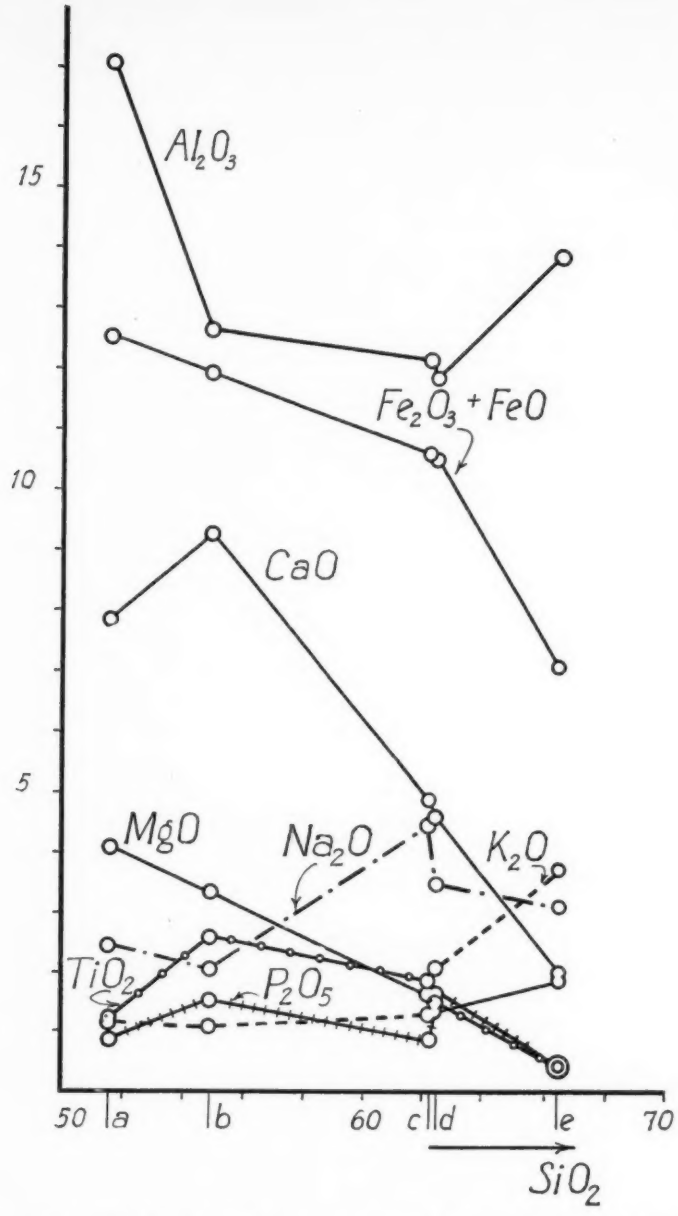

FIG. 6.—The chemical relations of the rocks of the intermediate zone. (*a*) Top part of basic member. (*b*) Most basic phase of intermediate rock, *A*. (*c*) Hybrid rock, *B*. (*d*) Most acid phase of intermediate rock, *C*. (*e*) Bottom part of acid member.

member—a transfer of which we have already had excellent examples in the association of granophyre and adinole elsewhere in the province. That this transfer has been brought about through the agency of the water in the magma there can be little doubt, and to the same action it seems most reasonable to refer the striking access of TiO_2 and P_2O_5 which these rocks have received. For further details of the mode of the reactions, however, we must look to the mineralogical and textural evidence.

b) *Mineralogy and texture.*—The first feature we may note about the rock types referred to in a previous section as *A* (the most basic variety), *B* (hybrid rock), and *C* (the most acid phase) is that, although their chemical composition is about that of the granodiorites or quartz-diorites, they show little or no textural resemblance to these rocks. In all of them we can distinguish an older set of minerals which have undergone alteration and have been replaced in part by later crystallizations which are of smaller grain size. The earlier minerals are plagioclase and amphibole, and the later ones, quartz, microperthite, biotite, blue-green to yellow-brown amphibole, white mica, apatite, epidote, titanite, and ilmenite. In the case of the most basic variety, *A*, the texture may be explained by considering that here we have as the main part of the mass the normal crystallization of the upper part of the basic member which, as shown in Part I, consists of plagioclase, hornblende pseudomorphous after pyroxene, and quartz with some microperthite. Though essentially solid, this mass contained many liquid interstices, and into these, replacing in part the normal residual liquid of the basic member, there came another liquid very rich in water, phosphorus, and titanium. From these small interstices this liquid worked outward into the already solid matter, bringing about metasomatic changes. Since the majority of these took place in the solid state, the resulting textures, like those of ordinary metasomatism, differ markedly from normal igneous ones. Perhaps the most remarkable textural feature is that shown by the new phase of the amphibole. This forms most intricate intergrowths with quartz, often of micropegmatitic appearance, and it is this peculiar relation which is one of the most noticeable departures of the rock from a normal igneous one. The newly forming apatite always appears as excellent crystals no

matter with what other minerals it may be associated. The alteration brought about in the plagioclase has been its conversion to epidote and white mica, but in many cases biotite, amphibole, apatite, and clusters of epidote crystals have also been added. There seems little doubt that the new liquid introduced at least some of the components of epidote for patches of the pure mineral are found quite apart from any other lime-bearing mineral.

In the case of the most acid variety, *C*, we have probably the other extreme from *A* so far as the ratio of earlier-formed crystals to new liquid is concerned. There are present here more calcic plagioclase crystals which probably represent those of *A* and like them are greatly altered. Associated with these, which we may term "foreign" plagioclase crystals, there is abundant biotite which the writer would interpret as a secondary formation after the earlier-formed hornblende of the basic member. As it occurs in patches and streaks between these foreign plagioclase crystals and also veins them, it is probable that the new liquid, which is essentially that of the acid member, has been in motion with these patches of a former crystallization within it.

The hybrid type, *B*, owes its abnormal texture to the fact that it represents (*a*) the metasomatic influence of the new liquid on the former crystallizations as in *A* and (*b*) the results of the intermixture of two saturated liquids, both of which probably contained a high concentration of water. The first aspect of the situation we have already considered, but the second we must now study in some detail.

These two liquids before admixture would be saturated with some solid phases, but these solids would not be the same in the two cases. Both liquids would contain also certain concentrations of dissolved water, but not only would these concentrations be different but the vapor pressures due to them would also probably differ. Finally, owing partly to these differences and partly to the contrasted chemical compositions, the temperatures of the two liquids would not be the same, that of the acid one probably being the lower. On account of these dissimilar properties, therefore, some marked changes of the equilibrium would take place on the intermixture of the two liquids. The first change would probably consist of a re-

partition of the amount of water dissolved in each with a further adjustment when liquid of intermediate composition was formed. With the movement of this component from one liquid to the other there would probably also be an accompanying distillation of some of the anhydrous components and to this transfer may be due the concentration of apatite and titanite in this hybrid rock. These new concentrations of the aqueous component would probably change also (*a*) the nature of the solid phase in equilibrium with the liquid and (*b*) the temperature of saturation itself. Thus, if, as seems probable, there was a movement of the volatile component into the more basic liquid, the already formed solid would now be out of equilibrium with it and resorption would take place. The immediate proximity of the acid liquid of lower temperature would, however, soon bring about saturation and the new solid phases, probably hydrated, would be precipitated. These relations would be altered again by the actual diffusion of the acid liquid into the basic one with the production of intermediate material, and here once more the nature of the solid phase in equilibrium with the liquid would probably change with consequent resorption and precipitation of new phases. It is evident, therefore, that the textures produced by such a complex process would differ radically from those of normal igneous material, and conspicuous among the mineral relations would be those of resorption, replacement, and concentration of new crystals about centers representing foci of reactions. Since, moreover, the equilibrium would be constantly changing, the grain size of the minerals produced would be small as each change of equilibrium would bring about relatively sudden saturation conditions. All these features are certainly shown by the hybrid rock, as can be seen by a study of the camera-lucida drawing of Figure 4, and for this reason it is concluded that this rock represents the admixture of the liquid of the acid member with that of the basic member, the latter containing at the time of mixing some crystals of calcic plagioclase and amphibole. That the admixture was imperfect is seen by the fact that the rock varies considerably from point to point and that there is no simple relation between the amount of micropegmatitic material and the proportion of ferromagnesian minerals. Since the substance of the latter was derived partly from the already

solid matter of the basic member, partly from the liquid of the latter, and partly from the acid liquid, it would be unlikely that its amount would bear a simple relation to the amount of acid liquid present as represented by the proportion of micropegmatitic material.

c) Distribution of types.—The other feature of the intermediate zone to be explained is the distribution of these various types within it. Since, as Figure 4 shows, there is no regular gradation from the acid material to the basic, it must be concluded that the liquids discussed above have been to some extent interbanded. As to the origin of this interbanding, there is little direct evidence in the rocks themselves unless it be that in the most acid variety, *C*, there is a suggestion of movement of the more acid liquid. If such a relation existed, a rather heterogeneous mixture of the various types would result. The partly solid basic member would not flow continuously but would take part in the movement as elongated lenses. At the same time, thin sheets of the salic liquid would penetrate the uppermost part of the basic member so that between the two typical rocks there would be developed a heterogeneous zone of streaked material. No sharp boundaries would, however, be apparent since both materials concerned were at least partly liquid and the whole process took place in an environment in all essentials plutonic.

It is to be concluded, therefore, that this intermediate zone represents the imperfect mixture of liquid acid member and partly solid basic member, the commingling having been due in part to the movement of the acid liquid over the other. In controlling the mineralogy and texture of the resulting products the presence of dissolved water in both liquids has been important, and to the distillation of this component from the acid magma is probably due also the concentration of soda, apatite and titanite in these intermediate rocks.[24] Having come to a conclusion then on these points, we may proceed to

[24] A. Harker, "Tertiary Igneous Rocks of Skye," *Geol. Surv. Scotland* (1904), pp. 181–82; H. H. Thomas and W. Campbell Smith, "Xenoliths of Igneous Origin in the Trégastel-Ploumanac'h Granite, Côtes du Nord, France," *Quart. Jour. Geol. Soc.*, Vol. LXXXVIII (1932), p. 289; S. R. Nockolds, "Some Theoretical Aspects of Contamination in Acid Magmas," *Jour. Geol.*, Vol. XLI (1933), pp. 561–89; "Petrology of Barnavave, Carlingford, I.F.S.–1. The Junction Hybrids," *Geol. Mag.*, Vol. LXXII (1935), pp. 289–315.

a consideration of the hypotheses outlined at the beginning of this section.

The possibility of the formation of the acid member through assimilation of sediments by the magma of the basic member was first suggested by Coleman,[25] but the only real attempt to follow it through to its ultimate conclusions was made later by Bain,[26] who based much of his work on studies made of the mass west of Sudbury described above. As this theory has already been discussed at length in separate papers,[27] it is not necessary to reconsider it here. There are so many major difficulties in its application that it cannot be said to offer any real solution to the problem, and we may therefore proceed at once to the other hypotheses.

If the acid and basic members have been derived by differentiation in situ from a homogeneous magma, the latter must have been of intermediate composition. This composition can be estimated if it be assumed that the relative areas of the acid and the basic members in the outcrop represent faithfully the ratios by volume of the two fractions of the mass. The original composition is then that given in column 3 of Table 4. As Bowen[28] has already suggested, however, this assumption may not be justified since differential movement of acid member to the upper parts of the basin may have taken place so that in the cross section now exposed to us the latter appears somewhat in excess of its true proportions. This differential movement could not have been very great since the heterogeneity one would expect from its operation is not present and the ratios given in column 4 of Table 4 probably represent therefore an absolute minimum for the proportion of acid members in the primary magma on this hypothesis, and we may then consider its composition

[25] A. P. Coleman, "Sudbury Laccolithic Sheet," *Jour. Geol.*, Vol. XV (1907), p. 773.

[26] G. W. Bain, "Amount of Assimilation by the Sudbury Norite Sheet," *ibid.*, Vol. XXXIII (1925), pp. 509–25.

[27] G. W. Bain, *ibid.*; "Evidence of Assimilation and Assimilation Processes," Vol. XXXIV (1926), pp. 657–70; N. L. Bowen, "Amount of Assimilation by the Sudbury Sheet," *ibid.*, Vol. XXXIII (1925), pp. 825–29; Phemister, "Criticism of the Application of the Theory of Assimilation to the Sudbury Sheet," *ibid.*, Vol. XXXIII (1925), pp. 819–24; "Evidence of Assimilation and Assimilation Processes," *ibid.*, Vol. XXXIV (1926), pp. 653–56.

[28] "Amount of Assimilation by the Sudbury Sheet," *op. cit.*, pp. 825–29.

as lying somewhere between the values of columns 3 and 4. The problem thus becomes one of judging whether or not it is possible for this liquid to give the relations we now find between the acid and the basic members.

It is to be noted first of all that this primary homogeneous liquid is of granodioritic composition, and to the geologist therefore the

TABLE 4

COMPOSITION OF THE PARENT MAGMA OF THE SUDBURY IRRUPTIVE

	1	2	3	4		5	6
SiO_2	54.64	67.85	62.89	60.69	Quartz	17.22	13.80
TiO_2	1.12	0.57	0.83	1.01	Orthoclase	16.68	15.01
Al_2O_3	16.70	13.06	14.86	15.46	Albite	27.25	27.20
Fe_2O_3	2.09	1.81	1.96	2.00	Anorthite	17.79	20.19
FeO	6.89	4.61	5.70	6.02	Diopside	.....	1.83
MgO	5.00	2.07	3.42	3.87	Hypersthene	15.89	16.33
CaO	7.11	1.51	4.02	4.95	Magnetite	3.02	3.02
Na_2O	2.98	3.36	3.24	3.19	Ilmenite	1.52	1.98
K_2O	1.65	3.66	2.82	2.50	Apatite	0.67	0.67
P_2O_5	0.39	0.17	0.26	0.31			
H_2O	1.53	1.27	.....	.....			
CO_2	0.16	0.16	.....	.....			
S	0.10	0.40	.....	.....			
Total	.....	.....	100.00	100.00			

1. Average composition of the basic member estimated from Walker's and Knight's analyses.

2. Average composition of the acid member estimated from Walker's and Knight's analyses.

3. Composition of the homogeneous parent-magma consisting of acid member, 55.6 per cent, basic member, 44.4 per cent, by weight, i.e., the ratios shown in the outcrop.

4. Composition of the homogeneous parent-magma consisting of acid member 40 per cent, basic member 60 per cent, by weight.

5. Norm of 3.

6. Norm of 4.

best answer to the immediate question is obviously to be sought in a survey of the larger granodioritic masses of the earth to see if any signs of a splitting into materials similar in composition to the acid and the basic members occurs. Such a survey shows that on the whole the great granodioritic masses are characterized by their extreme uniformity and that even in the cases where heterogeneity has been developed the products are not quartz-diabase and granophyre but hornblende-rich rocks and granite. This line of evidence

therefore indicates that it is improbable that the acid and basic members were derived from such a homogeneous liquid.

Since it may well be argued, however, that Sudbury is a special case and that here conditions were most favorable to this type of differentiation, it is therefore necessary to adopt a more physico-chemical mode of attack. Heterogeneity may develop in two ways: (1) by separation of immiscible liquids and (2) by differential movement of crystals and liquid. Regarding the first of these, we have evidence of the artificial melts which indicates that with liquids of the composition of the rocks of the type we are considering it is most improbable that immiscibility would obtain. Collins,[29] however, rightly putting the geological evidence before that of physical chemistry, favors this hypothesis, and we may consider his arguments at this point. He insists first that the "nickel irruptive" consists of a single igneous body, the main evidence for this being that nowhere is there a clean-cut contact between the acid and the basic members, though he does agree that these two parts of the mass are of very contrasted and distinct types. Next he points out that the so-called "offsets" are integral with the irruptive itself and represent injections from the sill-like mass into its floor. The rock of these "fins" he shows on textural grounds has crystallized from a liquid of essentially its own composition and this liquid was that of the basic member, so that the latter must have been formed prior to crystallization since refusion is not considered to have been possible. But if one reverses the order of this argument! The offset rock is noritic, was injected from the adjacent mass as a liquid, therefore the latter was itself a liquid at the time of its formation and, since it is of contrasted composition to the acid material on the inside of the outcrop, separated from it by an extremely narrow zone, probably entered the earth's crust at this point as a liquid of essentially its present composition. Before accepting any hypothesis involving liquid immiscibility, some positive evidence of its operation is surely necessary, and that evidence would lie in the presence of sharply bounded drops of the insoluble acid material in the "norite." Such evidence is certainly lacking, and the relations of acid

[29] "Life-History of the Sudbury Nickel Irruptive, I. Petrogenesis," *op. cit.*, pp. 123–77.

and basic materials as shown in the foregoing are of quite a different type. Clearly the two liquids were not in equilibrium with one another or with the solid phases present in each other and, as has been suggested, the relations indicate that the vapor phases were also out of equilibrium with one another. Until, therefore, some more positive evidence is forthcoming to offset the conclusions drawn from laboratory studies, we must look to fractionation of crystals and liquid for the development of heterogeneity in the mass.[30]

In order to carry out this study it is necessary to know the ratios of liquid to solid matter and the nature of the latter at different points in the crystallization-history of the magma. As an aid the composition as given in column 3 has been projected in Figure 7 into the four-component system (partly hypothetical), anorthite-albite-olivine-silica, and for the purposes of our analogy we may note these two points: (*a*) The composition of the first crystals to separate would be for the drawing $ab_{10}an_{90} = 56$ per cent; clinohypersthene = 44 per cent. (*b*) When the liquid had reached the composition *Q*, the solid-liquid relations would be about liquid = 82 per cent; solid = $ab_{40}an_{60}$, 13 per cent; clinohypersthene 5 per cent. From this point onward the amount of solid matter would increase rapidly, owing to the presence of the new solid phase.

In the early part of the crystallization it seems quite probable, therefore, that opportunities for the gravitational separation of the pyroxene would arise, and we should thus expect to find an enrichment in this constituent in the basal layers. It is improbable, however, that any similar concentration of early separating plagioclase would occur, for, since the specific gravity of the liquid would be about 2.75, the crystals would remain at the horizons at which they separated. The enrichment in pyroxene could never be very great as the amount of this mineral actually present would be very small during the earlier part of the crystallization. When, later, the amount increased, quartz would also be present and the ratio of crystals to liquid would have become so high that little or no settling could take place, as it seems improbable that, when the mass contained more than 25 per cent solid matter, any marked settling of any one

[30] See N. L. Bowen, *The Evolution of the Igneous Rocks* (Princeton), chap. ii, for a discussion of the question of liquid immiscibility.

constituent not in predominant amounts could occur. While, therefore, gravitational differentiation of the parent magma is possible, it is certain that the rocks so produced would not differ very much in composition and that furthermore there would be a general composition gradient from top to bottom of the mass.

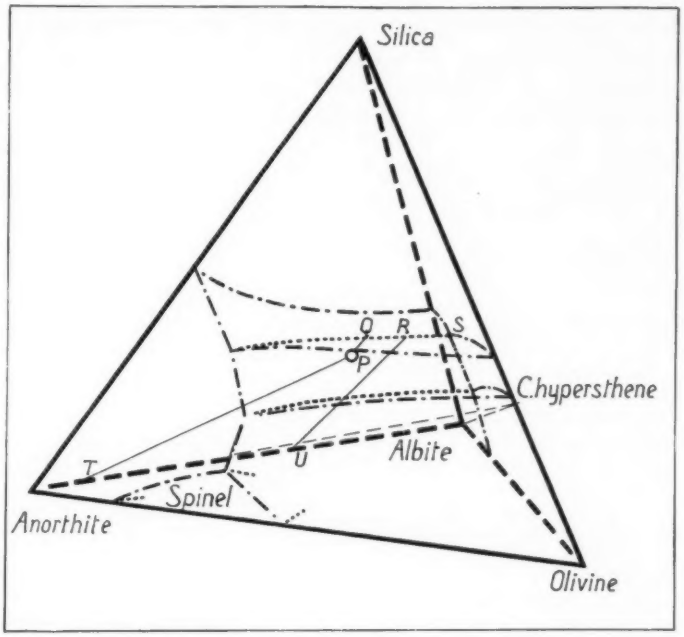

FIG. 7.—Hypothetical diagram of the system anorthite-albite-olivine-silica. *P* is the projection of the parent-liquid of the Sudbury rock into this system.

If we turn now to the field relations to see in how far they agree with what this study has led us to expect we find that this theory leaves practically all the major relations unexplained. In the first place, as already emphasized, the acid and the basic members are highly contrasted types and the narrow zone of intermediate rock between them does not show a regular composition gradient. Furthermore, if we plot the excellent series of analyses made of speci-

mens taken in traverses across the mass through the energetic studies of Knight and Walker, the absence of the regular variation in basicity from the bottom to the top of the rock is manifest. These curves are given in Collins' paper[31] and need not be repeated here. The curves show not only a sharp break between the acid and basic members but also indicate that the rock at the contact of these two bodies departs markedly from either of them and no process of "smoothing out" of the nodes is justified. Collins' graphs also, showing the variation of the specific gravity across the irruptive, fail to confirm the expectations of theory in this respect as there is a very

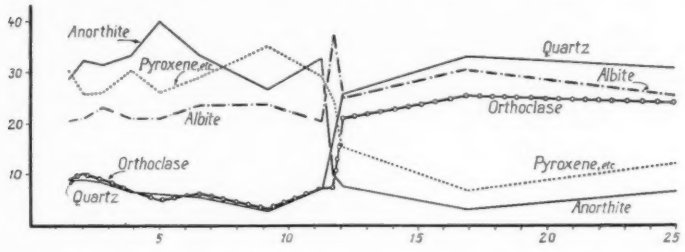

FIG. 8.—Curves showing the proportions of *normative* minerals across the irruptive north of Creighton. Drawn from Walker's analyses. The composition of the hybrid type, *B*, of Table 3 has been inserted. Compare this with the modal curves given by Phemister, *Ann. Rept. Ont. Dept. Mines*, Vol. XXXIV, Part 8 (1926), p. 16.

sharp maximum in the "norite" immediately below the intermediate zone.

The plotting of the absolute values for the various oxides is not, however, the most desirable way to test this hypothesis, since the latter is primarily concerned with the movements of crystals and in Figures 8 to 10 the variations in the "norms" are shown for the Creighton, Levack, and Maclennan traverses. The Creighton traverse crosses the irruptive at its widest section and the true width of the zone of intermediate rock is given in Figure 3. The relations shown by these curves, and by the others also, present insuperable difficulties to the satisfactory application of the theory of gravitative differentiation, in its simple form at any rate. The high content

[31] "Life-History of the Sudbury Nickel Irruptive. I. Petrogenesis," *op. cit.*, pp. 143–48.

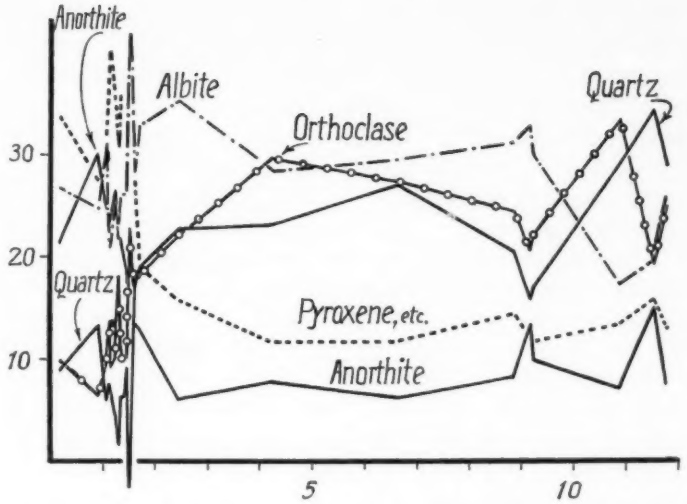

FIG. 9.—Curves showing the proportions of *normative* minerals across the irruptive in the Levack section. From Walker's and Collins' analyses.

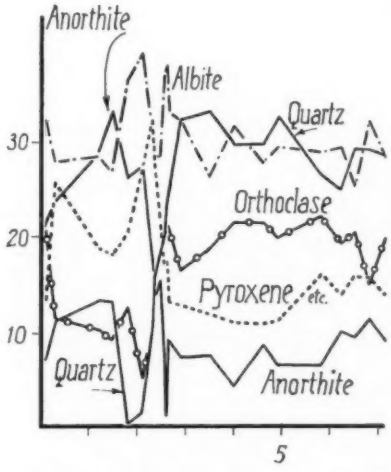

FIG. 10.—Curves showing the proportions of the *normative* minerals across the irruptive in the Maclennan section. From Knight's and Collins' analyses.

of anorthite about halfway across the basic member and the increase in pyroxene which it shows close to its contact with the acid member are facts entirely opposed to such a theory, as is also the almost universal increase in the proportions of quartz and orthoclase toward the base. With regard to the sharp break between these rocks also, it is to be remembered that the "transition zone," if such exists, is probably much narrower than shown in the curves for these samples, for analyses were taken only at the most convenient points and no special attention given to the exact delimitation of the zone.

If we endeavor to apply this hypothesis to the mass of similar rock to the southwest we meet with precisely the same difficulties. Here, again, there is no regular variation in basicity from top to bottom of the mass. The intrusion shows a very roughly banded arrangement of material of strongly contrasted composition and the most acid rock is certainly not on top.

Walker has recognized these difficulties to the hypothesis in its simpler form and he would explain the presence of the basic phase in the upper part of the basic member by considering that more rapid freezing of the lower part inhibited the complete settling of the early forming crystals of the heavier minerals, while a distillation upward of the volatile components so reduced the viscosity of the rest of the mass that the separation was greatly facilitated.[32] That such a process was operative is quite probable, and the writer has suggested that it is one possible explanation of the variations within the basic member itself and also within the sill at Cobalt.[33] But that it is able to explain the sharp separation of the large amount of granophyre, which is itself in greater amount than the so-called norite, hardly seems reasonable when the very essence of the theory is that freezing of the mass was proceeding from the cold margins. If the onset of a quasi-solid state was rapid toward the base, it would, under the conditions we are considering, be more rapid at the top, and we should therefore expect to find there material not much different in composition from the lower part of the basic member.

[32] T. L. Walker, "Magmatic Differentiation as Shown in the Nickel-Intrusive of Sudbury, Ontario," *Univ. Toronto Studies, Geol. Ser.*, No. 38 (1935), pp. 23–30.

[33] Phemister, "A Comparison of the Keweenawan Sill-Rocks of Sudbury and Cobalt, Ontario," *op. cit.*, pp. 121–96.

In any case this theory misses the fact that it is not simply a matter of explaining an increase in the specific gravity at the top of the "norite" but something much more difficult, high density along with an increase in the amount of Na_2O, not to speak of the details of the mineralogy and texture at this point.

Since gravity alone does not appear to have been the agent of fractionation, we may ask whether the separation of the more basic crystals from the liquid has been effected by some form of "filter-pressing." Bowen has already dealt in considerable detail with this process, so that we may proceed at once to the critical evidence. Straightway we see that, so far as the field evidence is concerned, there is little hope of distinguishing a heterogeneity produced in this way from one which is of a primary character, or from the results of the separate injection of the one magma on top of the other cognate one which was not yet wholly solid. In the three cases it will appear that the liquids have existed in contact with one another and, in all, some form of banding may be produced so that distinctions must be made on broader grounds.

Though it is not possible on this field evidence alone to decide between these hypotheses, yet on geological grounds there can be little doubt as to which are the least satisfactory. In the first place, it is clear that in the homogeneous parentmagma we have been considering the mass would be about 45 per cent crystalline when the liquid in the intercrystal spaces was of the composition of the acid member. It is very difficult to conceive of any method therefore of "filter-pressing" which would squeeze out this great amount of liquid and at the same time compact the solid which remained into the basic member as we now find it. In the second place, the distribution of the acid member throughout the outcrop is extremely uniform while the basic part of the mass varies considerably in width from point to point. Such a relation is the opposite of what we should expect had the granophyre been derived by deformation-differentiation from the crystal mesh of the basic member, for, as the stresses would vary from point to point throughout the basin, the acid liquid would be bound to be concentrated in those parts where the stresses were least. The perfect separation also into the two distinct bodies shows this hypothesis to be unsatisfactory, as,

again owing to the variation of stress throughout the basin, there must have been places where the separation was less complete than others and points also where the acid liquid was injected into material of approximately the composition of the primary magma. For these reasons, therefore, the writer feels that this hypothesis in its narrower interpretation is quite unable to account for the relations of the two rocks. If it is interpreted in a broader way, then it really becomes but an attempted explanation of the emplacement of two separate but cognate liquids, the more basic one of which was injected first and was followed by the acid one while it was still partly liquid.

The uniformity of the acid member and its sharp contact with the more basic rock is a stumbling-block also to the hypothesis of the origin of the rocks from a heterogeneous liquid. Even if we could conceive of the existence of an individual magma with such contrasted liquid fractions, we are still confronted with the difficulty of seeing how the sharp boundary between the two liquids could be maintained during the course of the intrusion of the mass into the crust. It would seem, therefore, that the only explanation of the relations lies in considering that the acid member was intruded as a separate and distinct magma on top of the partly solidified mass of the basic member, and we may proceed to consider briefly the petrogenetic significance of this relation.

The basic members as a whole must then have crystallized from a magma of its own composition. This is much more in line with the evidence which we have already gathered regarding the nature of the liquid which appears to have been tapped during this period. The composition of this magma is given in Table 1, and if it is compared with the average composition of the basic member as shown in Table 4, the general similarity is evident. One of the greatest theoretical difficulties to the idea of a parent magma of the composition of the Sudbury mass as a whole is that it introduces into this petrographic province a liquid entirely foreign to it, and one which seems to appear in the earth's crust elsewhere only in those regions which are being subjected to mountain-building forces. If, however, the basic member represents essentially the magma from which it crystallized, the integrity of the province is preserved.

The basic member then being a separate intrusion, two features have to be accounted for: (1) its somewhat more acid character compared to the general quartz-diabase of the region, and (2) its internal variations. It is impossible to consider these two topics quite separately since each is intimately connected with the other, but we may for convenience, start the discussion with the first.

In a previous paper the writer[34] has already suggested an explanation of this feature, but the new chemical data make necessary a reconsideration of these points. Taking all of the evidence we now have, the features which any theory must explain are these: (1) the presence of a broad band rich in calcic plagioclase from about one-half to three-quarters of the way across the mass; (2) an increase in ferromagnesian constituents close to the contact with the acid member, an increase which is controlled by the proportion of the ferrous silicate; (3) a decrease in free silica in many cases about three-quarters of the way across the intrusion; (4) an increase in quartz and alkali feldspar toward the base; (5) a concentration of Na_2O and of apatite, titanite, and epidote in the intermediate zone.

The most reasonable method of tackling this problem seems to be to assume first that the magma as intruded was homogeneous and to endeavor to see what sequence of events could bring about the variations which we now find. If such a hypothesis affords no reasonable explanation of these variations, the only conclusion which we can come to is that the intrusion, at least at the horizon now exposed to us, was not homogeneous before crystallization took place.

From the descriptions given it is clear that the first minerals to separate were non-diopsidic pyroxene and plagioclase, no olivine having appeared in this magma.[35] The plagioclase being about the same density as the magma itself would tend to remain where it formed, but the pyroxene would probably sink to lower levels if unhindered by the presence of other solid matter or adverse convection currents. Thus there might originate a lower layer richer in this earlier-crystallizing pyroxene, and this may be the explanation of the presence of hypersthene crystals in the vicinity of some of the ore

[34] *Ibid.*

[35] For a description of the details of the mineralogy, etc., see Phemister, *ibid.*

deposits. Such a settling of crystals must very soon, however, have been inhibited by the presence of the increasing amounts of solid matter as the writer has already shown to have been the case in the Nipissing diabase, so that any further differentiation must have occurred through the movement of interstitial liquid under the pressure of its own vapor in the manner suggested by Bailey.[36] This later stage of the differentiation process affords an explanation of the presence of quartz and alkali feldspar in the upper parts of the rock in many cases, and, since the late-forming liquid would also escape toward the lower margin, an explanation of the presence of these constituents at this horizon also. Neither of these modes of differentiation, however, provides an adequate explanation for the features (1), (2), and (3) heretofore noted, and the only conclusion we can come to is that the rock as we now see it represents the crystallization of liquids (or liquids carrying suspended crystals) of different composition. This heterogeneous mass may have entered the crust at this point as an individual magma or the heterogeneity may have been brought about by a series of injections of liquids of different composition.[37] The latter alternative, though by no means altogether disproved, is at least rendered less probable by the complete absence of any abrupt changes in the rock. Nowhere is there any sign of injection within the basic member, and the passage between parts of different composition is always gradational. It is probable, therefore, that the heterogeneity was a primary one and originated in the source of the Keweenawan magmas whence also must have come the granophyre. This is in agreement also with the evidence of the similar intrusion to the west. In it there is considerable variation in composition, and this variation does not show any regular transition from basic through less basic to acid, but consists in the juxtaposition of parts of marked difference in acidity.

Since we know the composition of the normal diabase magma evolved in this Ontarian province, it is of interest to see precisely what relation it bears to that of the Sudbury basic member as

[36] E. B. Bailey, "Geology of the Glasgow District," *Mem. Geol. Surv. Scotland*, pp. 186–88.

[37] Cf. Sir J. Flett, "The Teschnite of Eastern Dalmeny," *Geol. Surv. Great Britain, Summ. Prog.* (1929), Part III, pp. 59–74.

knowledge of this relation may throw light on the origin of the latter. In Figure 11 the composition of both are plotted along with that of

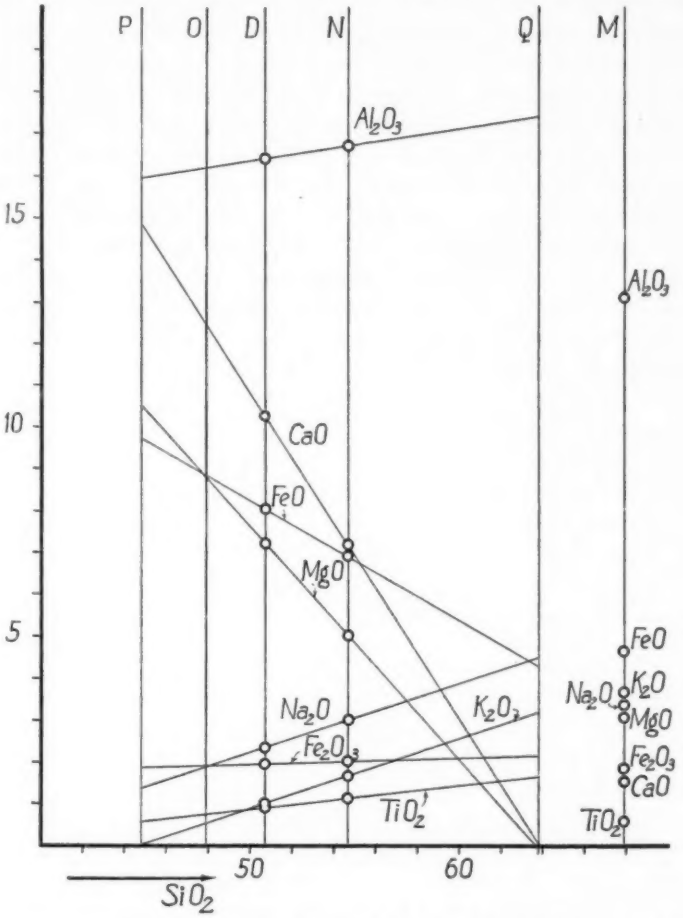

FIG. 11.—Diagram to show the relations of the Ontarian diabase magma, *D;* the basic member, *N;* and the acid member, *M*.

the average of the acid member. It was thought at first that the magma of the basic member might be simply an imperfect mixture

of the material of the Ontarian diabase magma and granophyric liquid, but the diagram shows that this cannot possibly be the case and therefore we can only hazard a guess at what the relations between the two magmas may be. The limiting compositions of the material which would have to be added to or subtracted from the diabase magma in order to give that of the basic member are given by *Q* and *P*, respectively. The norm of *P* shows it to be abnormal, but if the composition given by *O* be taken in its place, the relations

TABLE 5

RELATIONS OF THE MAGMAS OF THE ONTARIAN DIABASE AND THE BASIC MEMBER OF THE SUDBURY IRRUPTIVE

Normative Minerals	1	2	3
Quartz	23.34	.....	.....
Orthoclase	18.90	2.78	2.78
Albite	38.77	15.72	20.96
Anorthite	.....	34.72	28.36
Corundum	6.43	.....	.....
Diopside	.....	21.86	11.96
Hypersthene	3.43	12.51	12.22
Olivine	.....	6.01	9.18
Magnetite	3.25	2.55	5.34
Ilmenite	3.19	1.37	4.71

1. Norm of material to be added to the Ontarian diabase magma to obtain that of the basic member of the Sudbury irruptive.

2. Norm of the material to be subtracted from the Ontarian diabase magma to obtain that of the basic member of the Sudbury irruptive.

3. Norm of the Hebridean plateau basalt of Scotland.

become more comprehensible. The norms of these types *O* and *N* then are listed in Table 5. The material to be added corresponds generally to a leucocratic soda granite of no very definite type. That to be subtracted, however, is much more suggestive, for it resembles the type olivine-diabase magma which seems to be a stable species in the earth's crust, and for comparison the norm of the Mull plateau basalt of Bailey and Thomas is given in column 3. It is somewhat richer in lime than this widespread type but otherwise is essentially similar to it. Its relation to the Ontarian diabase magma and to the

basic member can be expressed thus: $N = 1.98D - 0.98O$, where N represents the basic member, D the Ontarian diabase, and O this olivine-diabase.

There is a suggestion, therefore, in this relation that the Sudbury centre of irruption has tapped a crustal horizon where parent diabase liquid, corresponding roughly to Washington's plateau basalt, has undergone some form of differentiation into a basic fraction, olivine-diabase, and a more acid one corresponding to the basic member. And in this connection it is of interest to note that the latest phase of pre-Cambrian igneous activity in this region was the formation of abundant olivine-diabase dikes of which we may take that cutting the rocks at the Murray mine as a type. The constituents of this olivine-diabase are all earlier crystallizations of the diabase magma, and as the ratios are about 1:2, it is further suggested that the differentiation has been effected by some such process as Balk[38] has described for the Adirondack mass or a deformational one in which the liquid has been expressed from the intercrystal spaces. Since such a process could hardly be of uniform operation throughout, a heterogeneous liquid, probably containing a considerable amount of suspended matter, would be the result and, though in its movement to its present site intermixing and diffusion would take place, these processes would never be sufficiently thorough to obliterate the original differences in composition.

ACKNOWLEDGMENT.—I cannot conclude this paper without expressing my indebtedness to Dr. W. H. Collins for his help and advice during our joint studies in the Sudbury district. On many sides of the work our views coincided, and, though on others a difference of opinion slowly appeared and became more marked with later discussions, his constant courtesy and consideration made possible that frank criticism without which any attack on these thorny problems would have been impossible.

[38] R. Balk, "Structural Geology of the Adirondack Anorthosite," *Min. und Pet. Mitt.*, Band XLI, Hefts 3–6 (1931), pp. 368–432.

PRELIMINARY NOTES ON EXPLOSIVE VOLCANISM IN SOUTHEASTERN MISSOURI

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ABSTRACT

Southwestern Ste Genevieve County, previously known as an area of igneous activity on a small scale, has been restudied. The known number of igneous occurrences has been increased from five to seventy-one, making the district comparable to those of similar type in Swabia and Scotland and unique in this country. Rock outcrops formerly described as sedimentary conglomerates have been recognized as débris-choked explosion tubes (diatremes).

The location of the volcanic area with respect to the broad regional Ozark dome and the more local Farmington anticline suggests a possible genetic relationship between these three geologic features. A physiographic high, coinciding in position with the volcanic district, demands attention and further study.

The igneous exposures, scattered over an area of about 75 square miles, are described as small bore-holes formed by gaseous explosions above a postulated magma chamber of laccolithic type. Mechanism of formation of the vents is discussed in considerable detail, as is a unique type of "autoclastic explosion breccia" found associated with individual pipes. Hydrothermal alteration, regional metamorphism, and mineralization receive only brief mention, detailed studies not being completed. The question of the age of the volcanism is given some consideration.

INTRODUCTION

The occurrence of post-Cambrian igneous rock in southeastern Missouri became generally known with the publication of a report by Weller and St. Clair.[1] This work revealed the existence of three recognized basic intrusives, eight small patches of "Tertiary (?) conglomerate," and two outcrops of rock of doubtful origin. More recently one of the basic intrusives was studied in considerable detail by Singewald and Milton.[2] They expressed the belief that the formation of the pipe was accompanied by explosive violence and lik-

[1] Stuart Weller and Stuart St. Clair, "Geology of Ste Genevieve County, Missouri," *Mo. Bur. Geol. and Mines*, 2d ser., Vol. XXII (1928). The county was divided by an arbitrary northwest-southeast line. The area of volcanism occurs in the southwest portion which was studied by St. Clair, the northeast half falling to Weller.

[2] Joseph T. Singewald, Jr., and Charles Milton, "An Alnoite Pipe, Its Contact Phenomena, and Ore Deposition Near Avon, Missouri," *Jour. Geol.*, Vol. XXXVIII (1930), p. 54.

ened it to a diatreme,[3] evidently little realizing that the district was actually perforated by a swarm of these vents and related dikes. Still more recently two additional recognized igneous exposures have been added to the list and one studied and described by Tarr and Keller.[4] These workers did not suggest an explosive origin for this latter occurrence although the evidence for such an interpretation seems to the writer very convincing.

During a short preliminary trip to the area in the spring of 1933 the writer recognized the "conglomerates" as being of volcanic origin and not sedimentary as they had been mapped. Two months were spent in the field during the summer of 1935. As a result many new pipes were found, the number known to exist being increased from five to seventy-one (Fig. 1). From the distribution of those found, the thickness and extent of mantle rock, and the ease of alteration of the igneous rocks it is concluded that the actual number of vents is far in excess of the seventy-one now known. Additional detailed field work will undoubtedly add to the number, though many more will probably never be located.

The type of volcanism is believed to be unique for this country and known on a comparable scale in but two other places in the world. Wilhelm Branca[5] in 1894 described a district in Swabia (Bavaria) where one hundred and twenty-seven *Vulcanenembryonen* or *Maare*[6] occur in an area of about 275 square miles. Their distribu-

[3] "Diatreme" (Greek, δια, "through," and τρῆγα, "hole") is a term suggested by Daubrée ("Les régions invincible du globe et des espaces célestes," [Paris: Bibliothèque Scientifique Internationale, 1892.) for vertical, cylindrical funnels or chimneys drilled through great thicknesses of solid rock by gaseous explosions, of which he mentions as an example the volcanic "necks" of the basin of the Firth of Forth described by Geikie in 1879. Daubrée, by artificial explosions, drilled small pipelike holes in solid granite which were not unlike "necks" and applied the results of his experimental researches to the elucidation of natural volcanic phenomena, giving the name "diatreme" to such explosion tubes.

[4] W. A. Tarr and W. D. Keller, "A post-Devonian Igneous Intrusion in Southeastern Missouri," *Jour. Geol.*, Vol. XLI (1933), p. 815.

[5] Wilhelm Branca, *Schwaben's 125 Vulcanenembryonen* (Stuttgart, 1894).

[6] Local term adopted from the native usage by Scrope in 1826. Its origin is doubtless explained by the fact that many of the occurrences of similar type in the Eifel region possess craters which are occupied by small lakes. The term "diatreme" is preferable, although it does not have priority, for the reason that the name suggests the mode of origin rather than topographic expression.

tion in a circular cluster, the doming of the sediments, the brief explosive character, and the abnormally steep thermal gradient led Branca to conclude that the area was underlain by a laccolithic ig-

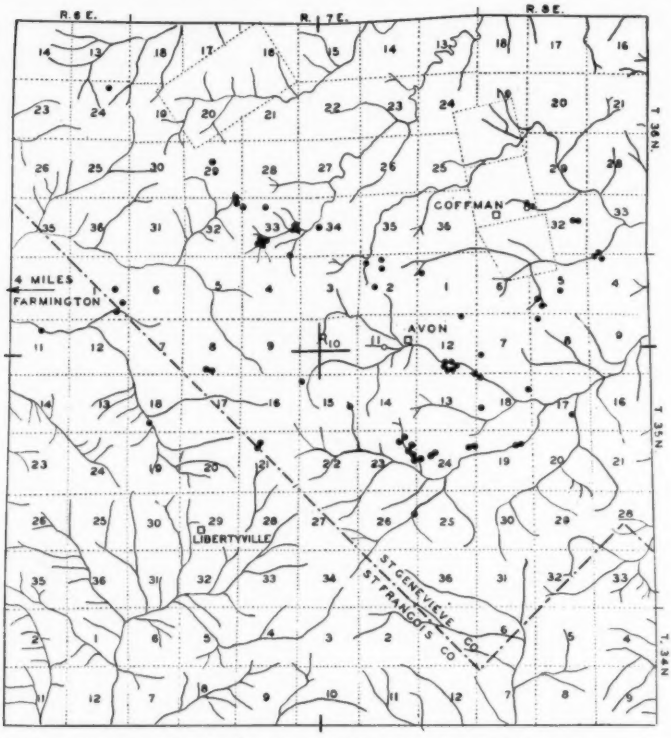


FIG. 1.—Key map showing locations of diatremes. Open circles are reported exposures not seen by the writer. Note radial drainage.

neous mass. In addition to the one hundred and twenty-seven so-called "tuff vents," there are five basalt plugs where erosion has cut deeply into the thick Jurassic sediments of the plateau.

The Carboniferous sediments in Scotland[7] have been perforated

[7] Sir Archibald Geikie, "Traces of a Group of Volcanoes in the Southwest of Scotland," *Geol. Mag.*, Vol. III (June, 1866). "Ancient Volcanoes of Great Britain," *ibid.*, Vol. II (1897), p. 69; "Geology of Eastern Fife," *Mem. Geol. Surv. of Scotland* (Glasgow, 1902).

by clusters of "volcanic necks" which suggest a mechanism of formation very similar to that which operated in Bavaria. There are three distinct clusters with a total of one hundred and sixty vents, the largest in southern Fife with eighty necks in an area of about one hundred and eighty square kilometers. Geikie's conclusion concerning the origin of these rocks is similar to that advanced by Branca for the larger district in Bavaria, namely, escape vents formed by gaseous explosions, renewed but not prolonged activity, and little or no extrusive lava. The later explosions seem to have followed the original tube, giving rise to agglomeratic types. This is at variance with the writer's interpretation of the Missouri occurrences where renewed activity is believed to have been expressed, in many instances, in the formation of new chimneys. Geikie and Branca took it for granted that the gases responsible for the explosions were wholly of juvenile origin. The possibility of contributions from the intruded sediments (resurgent gas) was not considered.

GEOLOGIC SETTING

STRUCTURE

The known post-Cambrian igneous exposures in Missouri occur in a large cluster centering near Avon (10 miles due east of Farmington). They occupy a circular area of about 75 square miles. The pipes are distributed unevenly over the southern part of Ste Genevieve County and to a lesser degree north and west of Libertyville (Fig. 1) in St. Francois County. This places the center of activity on the south limb of the local Farmington anticline (Jonca dome) which occupies the southwestern half of Ste Genevieve County. The possible relationship between the igneous activity, the Farmington anticline, and the Ozark uplift seems worthy of consideration (Fig. 2).

If we try to visualize the appearance of a paleo-structure map of southeastern Missouri at the end of Lamotte time, we would probably note structure-contour lines closing about the pre-Cambrian land mass now marked by the St. Francois Mountains. This apparent dome would be the natural result of initial depositional dip. The overlying Bonneterre dolomite would assume this dip of the sandstone surface and to it would be added that owing to differential

settling about buried hills.[8] This latter process would be operative on all overlying formations, but with rapidly decreasing effect as deposition went on. The erosion of such a pseudo-dome and the exhumation of the buried granite "hill" should produce an outcrop pattern characterized by rings encircling the original land mass. An examination of Figure 2 will show that with regard to the Bonneterre

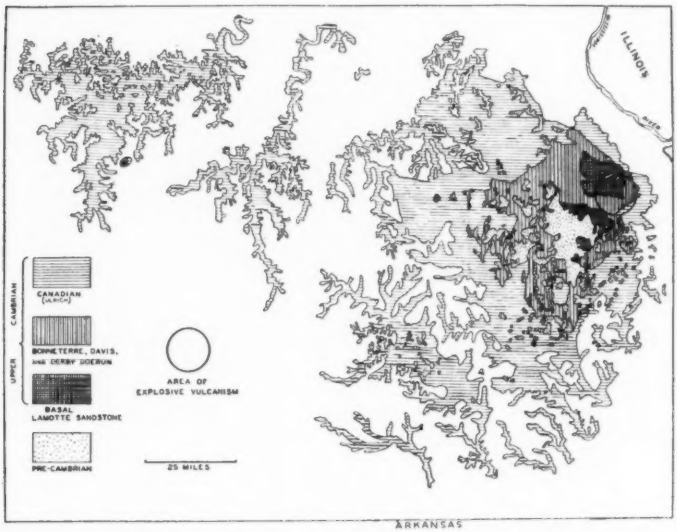


FIG. 2.—Generalized areal map of southeastern Missouri, showing relationship between igneous activity, Farmington anticline, and Ozark dome.

and younger formations this general relationship is true, but that the older Lamotte sandstone only outcrops on the north and east of the exhumed hill, and that processes of degradation, therefore, do not alone account for the Lamotte sandstone being exposed at all. Regardless of whether we consider the origin of the exceedingly broad and flat Ozark dome to be that of a "buried hill" or to minor orogenic movement, we must admit that there has been local arching of a diastrophic nature (the Farmington anticline) within the limits

[8] C. L. Dake and N. P. Bridge, "Initial Dips Peripheral to Resurrected Hills," *Mo. Bur. Geol. and Mines 55th Biennial Rept.*, Appendix A.

of the Ozark dome. It is this folding and faulting (followed by erosion) and not the unroofing of a positive physiographic form which would seem to account for the outcrops of Lamotte sandstone. The formation of the Farmington anticline by arching of the sediments on the flanks of the postulated pseudo-dome would result in an increase in dip of the sediments on that side of the local structure away from the early Cambrian land mass (pre-Cambrian granite and rhyolite hills). Between the local structure and the center of the original pseudo-dome there would be a decrease or even a reversal of dip. Therefore such arching, followed by erosion, would result in an outcrop pattern extended along a line connecting the small dome and the original "buried hill." Thus the formation of the Farmington anticline (regardless of cause), followed by erosion, not only accounts for the area of basal Lamotte sandstone outcropping in southwestern Ste Genevieve County (Jonca dome) but also for the Lamotte exposures found immediately to the northeast of the pre-Cambrian granite area (Fig. 2). That a belt of younger sediments separates these two outcrop areas of Lamotte sandstone is doubtless due to the thickening of these younger formations to the northeast and away from the buried physiographic high.

If the "buried-hill structure" idea seems inadequate to explain the Ozark dome and if one prefers to subscribe to a theory of arching by orogenic movements, then it is suggested that the stratigraphic and structural center of this regional arch is not, as commonly thought, the pre-Cambrian granite area centering near Ironton but should be identified with the area of folding and faulting which marks the Farmington anticline some 25 miles to the northeast. The near coincidence of this structural center, thus identified, with the area of igneous activity indicates the possibility that the area of explosive volcanism is a local manifestation of more deep-seated igneous activity on a larger scale which is responsible for the regional uplift.

The area of igneous activity is seen (Figs. 2 and 3) to be somewhat displaced from the top of the local Farmington anticline, but this lack of coincidence appears much less conspicuous and of little significance when the two are viewed as parts of the extensive Ozark dome. Any opinion regarding the possible causal relationship be-

tween the igneous activity and local and regional structure can admittedly be only conjectural. However, the idea seems attractive. If they can be related with regard to time as closely as they obviously are with respect to location, the argument will be greatly strengthened. Weller and St. Clair[9] state that the Farmington

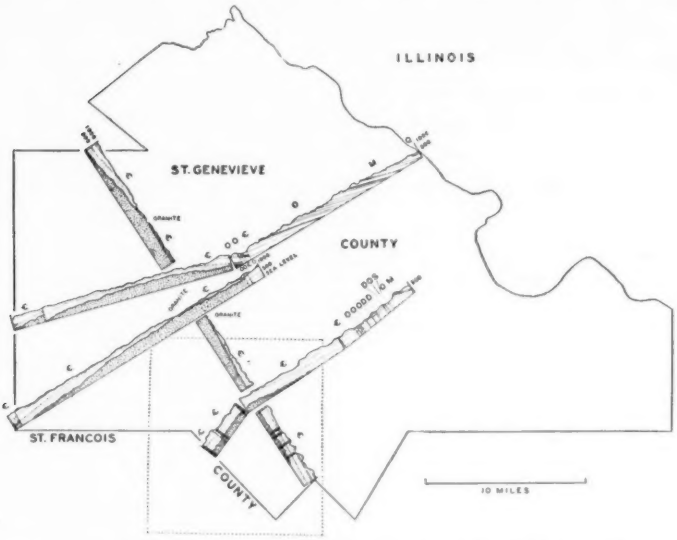


FIG. 3.—Generalized structure map showing position of Farmington anticline with respect to area of igneous activity (outlined by dotted line). Vertical exaggeration about 5 to 1.

anticline dates back to Bonneterre time. If such is the case the igneous activity, which we know to be at least post-Devonian, cannot be related to the structure. The evidence,[10] however, is not overconvincing, and the writer prefers, for the present at least, to cling

[9] *Op. cit.*, p. 273.

[10] Variations in lithology and thickness of formations immediately above the Bonneterre dolomite on opposite sides of the anticline. There are other ways of explaining these variations, such as changes in ocean currents. Extensive faulting, some of which might reasonably seem to be related to the anticline, is known to have occurred at the end of Devonian and in post-Pennsylvanian time, but none is recognized as being Cambrian in age.

to the belief that the near coincidence of these two geologic phenomena is more than accidental.

PHYSIOGRAPHY

The area of explosive volcanism is marked by a physiographic high. The top of the low, rounded divide, indicated by quaquaversal

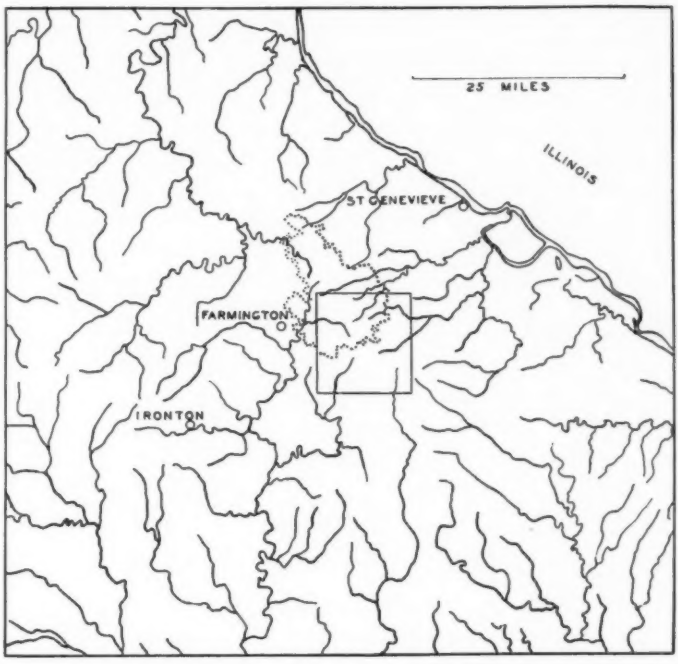


FIG. 4.—Map of southeastern Missouri showing quaquaversal drainage away from area of igneous activity. Note position of Farmington anticline (dotted line incloses La Motte sandstone outcrop).

drainage, coincides remarkably with the center of distribution of the diatremes (Fig. 4). The local physiography within this area is rather diverse. It varies between youthful, rugged, timbered hills and mature, rolling farm lands. The lack of uniformity in the topography is related somewhat to the bedrock character but more

closely to the direction of flow of the streams cutting headward into the rounded divide. Those streams flowing to the north and east, and rather directly to the nearby Mississippi River, have high gradients and deep youthful valleys. Maximum relief in this watershed amounts to as much as 500 feet. Where these northeast-flowing streams cross Bonneterre dolomite outcrops the topography is locally subdued. The streams which flow to the south and west, and by more circuitous routes to the Mississippi River, occupy more mature valleys in rolling farm lands. There is a striking suggestion of a direct relation between the development of the drainage pattern in this part of the state and the location of the site of volcanism. It might be said that the drainage is related to the Farmington anticline, which in turn may or may not be associated genetically with the area of igneous activity. An examination of Figure 4, however, will show that the location of the physiographic high, as revealed by the drainage pattern, is more closely associated with the cluster of vents than with the position of the Farmington anticline, but that all three are quite possibly related in origin.

If the quaquaversal drainage is to be associated with the area of volcanism, the question arises as to how they are related. It seems probable that it is a matter of stream adjustment to an area of superior resistance, this regional metamorphism having been effected by the igneous activity.[11] A number of alternative explanations appear untenable when it is known that at least 3,000 feet of sediments have been eroded from the district since the igneous activity occurred.[12]

IGNEOUS ACTIVITY

PRE-EXPLOSIVE DIKES

Of the seventy-one igneous-rock exposures a few are dikelike in form, are free from fragmental inclusions, and suggest a mechanism of emplacement unaccompanied by explosive violence (Fig. 5).

[11] More detailed information on the question of abnormal induration of the sediments is in progress and will be included in a later paper dealing with the petrology and mineralization.

[12] The presence of Devonian fossils, first noted by Weller and St. Clair (*op. cit.*, p. 248) in the "conglomerates," was more recently observed by Tarr and Keller (*op. cit.*, p. 815) in the fragmental material of a recognized igneous plug, at the intermediate Lamotte (Cambrian) sandstone horizon.

None of these dikes is traceable for any great distance laterally, and all appear to be of a thick, lenticular shape. They are all lamprophyric rocks and of similar mineralogic composition, although extensive alteration makes petrographic studies exceedingly difficult.[13]

FIG. 5.—Pre-explosive dike rock, mineralized (mostly carbonate) along shear planes parallel to contact with later explosion tube. ×⅔.

See the section on "Mechanism of Formation" for more details on the relations between these early dikes and later explosive phases.

EXPLOSION TUBES—DIATREMES

General Description.—There is a complete absence of any topographic expression that can be associated with the individual pipes or dikes. Processes of denudation have affected the volcanics at much the same rate as the enclosing rocks, which are sandstones and dolomites. This fact is doubtless owing, at least in part, to the extensive hydrothermal carbonatization which the igneous rocks have undergone. As already stated, the area of igneous activity possesses a rather diversified topography and whether emerging on steep or

[13] An excellent description of the petrography of one of the pipes has already been given by Singewald and Milton (*op. cit.*, p. 54).

gentle slopes, flat divides or stream beds, the explosive pipes and dike rocks are all essentially flush with the enclosing rocks. Thus the pipes and dikes can be located only where bedrock is exposed or where the soil mantle is comparatively thin and float is present on the surface. In most cases the igneous rock does not yield much loose float. Exceptions to this general rule were noted where the diatreme or dike emerges on a steep slope or where the fragmental débris of an explosive type was incorporated in a glassy matrix. In the latter case the included xenoliths yielded to weathering agencies

FIG. 6.—Typical "conglomeratic" diatreme rock

more rapidly than the matrix, thus giving to the rock a characteristic appearance not unlike scoria.

The explosive rocks are conspicuously varied in appearance and composition, but all have enough in common to make recognition not impossible when one has seen enough of the outcrops and has become familiar with the variations. The most characteristic feature of these extraordinary rocks is their striking conglomeratic appearance (Fig. 6). This feature makes identification in many cases relatively simple. One of the most difficult types to recognize in the field is that which was nearly or entirely fragmental and has been thoroughly indurated by carbonatization. This type possesses an

obscure breccia texture and is composed almost entirely of carbonate rock. This breccia texture is best revealed by differential weathering of inclusions and carbonate matrix. An occasional piece of granite in such types adds to ease of identification, as does also slight lithologic variation of the carbonate fragments.

In ground plan the diatremes are for the most part rudely circular or oval and, in general, possess vertical walls of undisturbed sediments. Although in most instances the contact of the diatreme rock with the sediments was not well exposed, where observed it was very sharp. Dynamite blasting was frequently resorted to in an effort to obtain better specimens. In one instance the charge was set off in a drill hole which was placed near the contact. The resulting small pit revealed vertical walls that had been intruded by thin apophyses of igneous material. These stringers are up to an inch in thickness and are seen to be both parallel and transverse to the bedding and to extend but a few inches into the walls. The extent of these wall-rock invasions was doubtless limited by the viscous character of the intrusive material. This is seen to be choked with an abundance of megascopic and microscopic foreign débris. Contact metamorphic effects, in many cases totally lacking, are never visible more than a few inches from the contacts.

In size there is no uniformity, the smallest diatreme being only a few yards in diameter and the largest observed about 300 feet across. In a number of instances there seems to be an association between the location of diatremes and faults. More detailed information concerning this relationship will be given later in the section on "Mechanism of Formation."

The fragmental included material varies greatly in amount in the different pipes, some pipes being almost free from foreign débris, whereas the rocks of others are entirely fragmental and without igneous matrix. The latter type is of less frequent occurrence than those with igneous components, and, as stated above, its rocks are indurated by extensive carbonatization. Megascopic included débris consists for the most part of angular pieces of limestone, dolomite, shale, chert, sandstone, and granite (Fig. 7). In thin sections the sandstones are represented by isolated and well-rounded sand grains and the granites by angular grains of feldspar and quartz. In a few

of the tubes concentration of this disintegrated granite gives the rock a light-gray color, suggesting a rhyolitic composition. More than casual observation, however, indicates that this apparent rhyolitic composition is due to extreme fragmentation of the intruded granite by explosion and not to any appreciable variation in the composition of the magma responsible for the formation of the vents. Variety of size as well as composition is a conspicuous feature of the included débris. The individual pieces range in size from dust particles and sand grains to large xenoliths as much as 10 feet across. Still a third prominent variation in the character of the material filling the vents is in the relative amounts of the different rock types

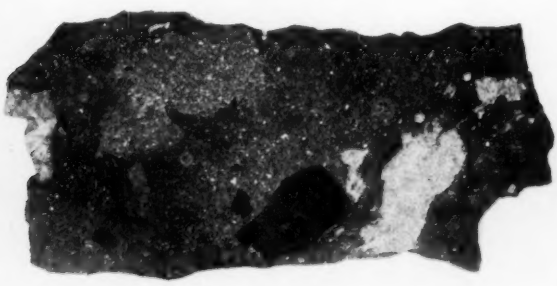


FIG. 7.—Hand specimen of diatreme rock showing fragmental inclusions. ½ natural size.

comprising the xenoliths. The possible significance of this variation will be considered later. In a few outcrops the rock carries rounded, dark-colored lapilli pellets ranging in size from mere specks to an inch across. These are mixed with a variety and abundance of angular xenoliths all incorporated in an igneous matrix. In other instances there is a concentration of these pellets with little or no sedimentary débris.

Mechanism of formation.—There is every suggestion that these peculiar igneous occurrences represent escape vents punched through several thousand feet of solid rock by gaseous explosion. An alternative hypothesis which might seem to warrant consideration is that these small circular exposures are non-explosive bore-holes formed

by a rising column of magma forcing its way by direct pressure and perhaps aided by overhead stoping and gas-fluxing. The xenolithic material would then represent rock fragments broken from the walls and carried upward. Consideration of certain facts, however, casts doubt on the validity of the latter interpretation. It is very common to find limestone fragments carrying Devonian fossils in a rock which also contains an abundance of granite inclusions. The granite pieces have come up several hundred feet and the Devonian fossils are at least 3,000 feet below their source beds. These two rock types, normally separated by about 4,000 feet of sediments, are found side by side at the intermediate Cambrian horizon of the area. Thus any theory of origin of these rocks must account for granite rising and limestone falling before coming to rest upon solidification of the magma matrix. If we appeal to a process of settling of the Devonian limestone fragments to a lower horizon in the magma tube, it then becomes difficult to explain how granite of approximately the same density would rise under those conditions. In fact, it is almost certain that in a magma of such ultra-basic composition both limestone and granite would readily float, thus making it impossible for fragments to get below their source beds if the tube was filled with magma. Nor does this process account for the high degree of fragmentation of much of the included material. Under the explosive hypothesis, however, fragments from the walls would be blown up or out and those that fell back might be of any size and found at any horizon.

Again, if we should picture the tubes being punched out by slow non-explosive forces, we would expect the sedimentary beds to be arched near the contacts much as they are around salt domes. Instead the sediments are most commonly flat-lying and undisturbed at the contacts (non-contradictory exceptions described later under "Explosion Breccias"). This fact alone suggests a force acting very suddenly, as does also the extreme fragmentation of much of the included material.

If we think of a magma column rising by overhead stoping and gas-fluxing alone, we should not expect the included materials to accumulate to a point of complete exclusion of the igneous matrix. Where the rock is without the more normal igneous matrix, it still

carries granite fragments. If we picture a débris-choked tube formed by explosion and the infall of shattered rock, all appears clear and logical. The rising column of magma, boiling and spurting at the surface and working against a descending swarm of angular, broken-rock fragments, would incorporate this débris in varying amounts which would reach a maximum near the surface. The distance that the rising column of magma invaded the fragment-filled tube would be limited by cessation of movement owing to the matrix cooling under the influence of the included fragments and the wall rock. Those outcrops which are composed solely of fragmental materials and are free from igneous matrix would thus represent a section of a débris-filled tube in which the incorporating magma had not risen to the level of the present surface. In other instances, where there are only small amounts of débris in the igneous rock, the eroded section now exposed either represents a section below that at which the rising magma column met the descending mass of débris following explosion or the clastic material was carried to higher levels by a rising current of viscous magma. That the latter process was effective, in certain instances at least, is very clearly shown in one excellent exposure. Here the outcrop is characterized by a ring of conglomeratic material (carrying boulders up to 3 feet across) with a diameter of about 60 feet. This outer phase is seen to encircle a central core which is about 25 feet in diameter and is free from megascopic fragmental material. The contact between these two phases is gradational and some vertical shearing has occurred in this intermediate zone. The central core carries an abundance of small feldspar fragments obviously derived from disintegrated granite. Parallel alinement of long axes of feldspar fragments and of phenocrysts from the magma gives the core rock a conspicuous flow-line texture. Here it is very clear that much coarse débris from the central zone has been carried to higher levels by the viscous magma current. The rapidly cooled border phase (the wall rock is a porous, water-bearing sandstone) became solid quickly enough to resist this upward pressure.

In an earlier section reference was made to several exposures which are characterized by the presence of variable amounts of rounded pellets in the explosive rocks (Fig. 8). Detailed study of

these unusual rock types reveals some particularly interesting features bearing on the origin of the pellets and the general mechanism of formation of the tubes. The rounded pellets, which vary in size from less than 1 mm. to over 3 centimeters in diameter, frequently have a nucleus of some sort. In some outcrops these kernels are predominantly phenocrysts from the parent-magma (Fig. 8). Elsewhere they are almost all angular fragments derived from broken granite. These vary in size from small microscopic microcline xeno-

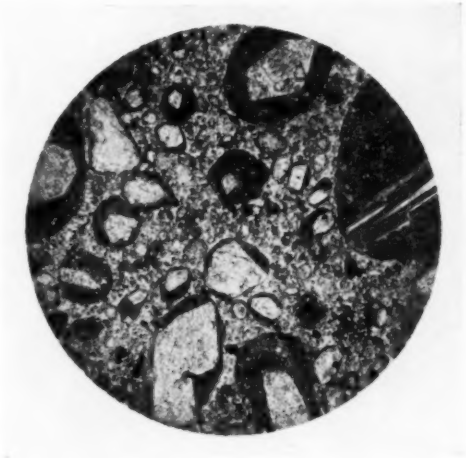


FIG. 8.—Explosive pellets (lapilli) incorporated in an igneous matrix. Note predominance of nuclei of pellets are phenocrysts from parent magma. ×10.

crysts to angular pieces of solid granite up to an inch across (Fig. 9). In other instances the nuclei are composed of fragments of the perforated sediments. Although the fragmental débris in these rock types includes huge boulders and all intermediate sizes, it is only those fragments which are less than approximately an inch in diameter that are seen to form nuclei of the pellets. Furthermore, there is no apparent close relationship between form and size of the pellet and the shape and dimensions of the kernel. The pellets are all round or oval regardless of whether the nucleus is equidimensional or lathlike (Fig. 10).

FIG. 9.—Diatreme rock carrying numerous lapilli. Kernels of lapilli are composed of phenocrysts or angular fragments of pre-explosive dike rock, granite, etc. $\frac{2}{3}$ natural size. Water immersion.

FIG. 10.—Pellets showing slight elongation when nuclei are lathlike fragmental feldspars derived from granite as contrasted with circular pellets which carry more equidimensional phenocryst nuclei. ×10.

Degree of crystallization is another variable which is characteristic of the pellets. This is to be expected and agrees well with the belief that closely associated vents were not formed at the same time. There are some pellets which are finely crystalline to glassy (Fig. 11), whereas others show an advanced state of crystallization with large pyroxene phenocrysts and a groundmass crowded with smaller feldspar laths (now altered to carbonate) and crystals of titaniferous

FIG. 11.—Explosive rock carrying pellets (note black, glassy variety as well as more normal finely crystalline type) incorporated in a tufflike mass of sand grains, angular to lathlike feldspar fragments (from granite) and fine carbonate débris. ×10.

magnetite (Fig. 12). In an intermediate type the feldspar laths are absent (Fig. 8). In many of the pellets the feldspar laths, when present, are oriented in a position parallel to the periphery of the pellet and to the surface of the nucleus body (Figs. 13 and 14). The explanation of this peculiar alinement of feldspar crystals is doubtless closely linked with that of the origin of the pellets. The writer's explanation of this characteristic orientation agrees with his tentative interpretation that the pellets were formed much as lapilli. The matrix for the pellets, so formed, would be variable in composition. It might be the post-explosive incorporating magma; it might be

fragmentary granitic or sedimentary débris, or, what seems more probable, a combination of the three types of material. Singewald and Milton,[14] after making a detailed study of one of these pipes, observe that the pellet-bearing rock seemed to be a contact phase. They express the belief that these pellets with their carbonate matrix (in other pipes the matrix is mineralogically heterogeneous) were formed by the break-up of the magma into droplets as a consequence of explosion and release of pressure. The localization of the

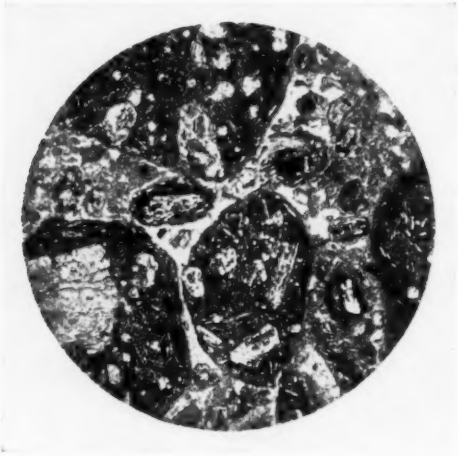
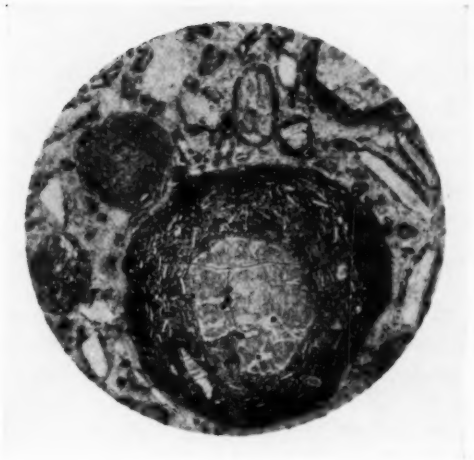
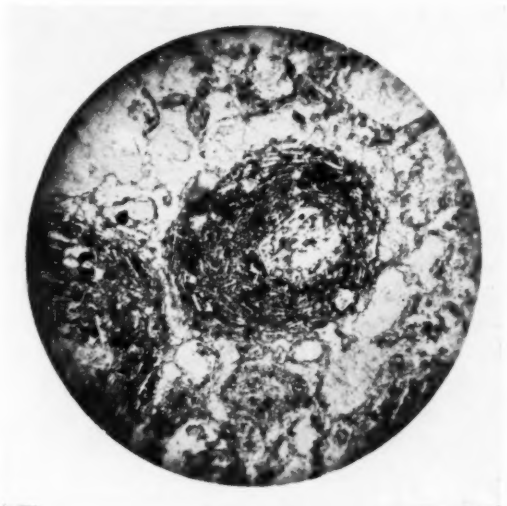


FIG. 12.—Igneous pellets showing advanced degree of crystallization. The small lath-shaped crystals forming the groundmass for the phenocrysts in the pellets are feldspar laths—now largely altered to carbonate. ×10.

pellet-bearing rock near the carbonate contact and the handicap of observations being limited to one outcrop, which was relatively devoid of many complicating features possessed by other diatremes in the cluster, led these workers to reach a somewhat different interpretation than that chosen by the writer, who was favored with a large number of exposures. The explanation of the localization of the pellets near the contact is that the entire tube at this horizon was originally filled with this contact type of material. Following explosion the tube doubtless became filled with infalling fragmental car-

[14] *Op. cit.*





FIGS. 13 and 14.—Explosive pellets (lapilli) showing characteristic orientation of lath-shaped crystals parallel to the perifery of the pellet and to the surface of the nucleus body. ×15.

bonate débris and igneous pellets. A rising and incorporating column of magma lifted and carried to higher levels all except the contact phase which had solidified quickly under the cooling influence of the wall rock. One outcrop has already been described where such relationships are clearly visible. Later extensive hydrothermal carbonatization has added much to that derived from fragmentation of the perforated sediments. As stated above, the matrix around the pellets is not always wholly carbonate but may be quite variable in composition. For instance, in one occurrence, the matrix, while containing much carbonate, carries such an abundance of magnetite crystals as to indicate its dominantly igneous nature, and that the carbonate is partly fragmentary and partly hydrothermal. In another case the matrix, while somewhat devitrified and altered, appears to have been originally glassy. In still a third, and perhaps the more significant instance, the pellets are fewer and less evenly distributed and are incorporated in a heterogeneous mass of microscopic and tufflike fragmental material consisting of dustlike particles, disintegrated granite débris, well-rounded sand grains, and megascopic rock fragments of all kinds (Fig. 11).

The roundness of the pellets indicates that they were solid when entombed in their present position. This implies that they solidified while suspended in a liquid or gaseous environment with a rapidly cooling influence. This sudden cooling was doubtless the effect of expanding gas, the obvious direction of expansion being upward and the ultimate cause of a blowout to the surface. The pellets were probably projected upward, possibly to the surface, becoming completely solid before being incorporated in the débris of the vent. If the feldspar laths had crystallized during or following formation of the pellets, they would have been oriented radially and not parallel to the periphery. Therefore they must have crystallized before explosion and have formed a slushy groundmass for the much larger phenocrysts which frequently form nuclei of the pellets. The factor responsible for the orientation of the feldspar laths must have been operating on crystals already present and during the short interval when the pellets were identifiable as such, but before solidification. This limits the possibilities very much. At the beginning of the explosion the solid particles now represented as nuclei of the bombs

were doubtless thrown into a space clouded by a spray of liquid magma. Projection of a solid particle usually gives it a certain amount of spin. Even the slightest rotation of the solid particles while the liquid coalesced about them would tend to move the linear crystals into a position roughly parallel to the rotating surface. Many pellets, however, did not have nuclei, and an occasional phenocryst nucleus is surrounded by unoriented laths. Some nuclei doubtless escaped this rotating influence. Linear fragments, if given a rotating movement about an axis that happened to be a short dimension of the object, would possess an end-over-end motion that would not orient the crystals in any regular fashion. Some pellets, as indicated by Figure 8, do not have feldspar laths to be oriented, and others doubtless do not show the characteristic orientation because the section was cut near and parallel to the axis of rotation.

An interesting feature of the distribution of the diatremes is the fact that they commonly occur in groups of two, three, or more. Some of these are no more than a hundred yards apart and separated from each other by flat-lying, essentially undisturbed sediments. This would seem to preclude the possibility of their having formed at the same time. In other words, the undisturbed sediments between the tubes (in one case about equal in thickness to the diameter of the tubes) would not have remained intact if both blowholes had formed at the same time. The first had undoubtedly solidified and cemented up before the accumulating gas pressure became great enough to punch through again. If we employ the principle advanced by Morey[15] that the crystallization of a system composed of volatile and non-volatile components is accompanied by generation of enormous gas pressures, we can understand why there was a renewal of explosive violence and the consequent formation of two or more tubes close together and above the same gas-gathering cupola. A small amount of crystallization may cause a very great increase in gas pressure. The porphyritic character of the matrix portion of the rocks indicates that crystallization was well advanced before explosion. If crystallization, however, was not far advanced when the first explosion occurred, then continued crystallization in the magma

[15] G. W. Morey, "The Development of Pressures in Magmas as Result of Crystallization," *Jour. Wash. Acad. Sci.*, Vol. XII (1922), pp. 219–30.

chamber might generate enough gas to cause additional blowouts. Different degrees of crystallization are clearly evident in the thin sections.

In an earlier paragraph the possible genetic relationship between the location of the pipes and nearby faults was suggested. Poor exposures make it difficult to prove that this association is general. Likewise it will require more detailed field work to demonstrate whether or not, within the area of igneous activity, there are appreciable numbers of lines of major displacement without associated dikes and pipes. It is believed that with continued erosion the number of non-explosive dikes would increase appreciably. Of the seventy-one igneous exposures twelve have been classed as non-explosive dikes and of these twelve half occur along conspicuous fault lines and the remaining half under conditions which make it difficult to state whether faults exist or not.

It seems reasonable to assume that the emplacement of the parent-laccolithic (?) igneous mass was accompanied by some adjustments in the roof. Such adjustments, if exposed as fractures and faults, would constitute leaks and hence effective channels for dike intrusions. Solidification of these bladelike and doubtless wedge-shaped dikes would transform the magma chamber into a closed system, preventing further leakage through the roof. The dikes would probably become thicker near the junction with the main reservoir. Crystallization would begin at the top and the thinner edges and proceed downward, with a resultant crowding of liberated gases downward and into the thicker portions of the dike near the reservoir. In such a manner might arise a gas-gathering cupola. The confined gas would accumulate to a point where the strength of the roof was exceeded. If this gas caused fluxing of the walls in accordance with Daly's hypothesis and if the dike had a slight dip, a gas-fluxed tube would branch off from the dike and grow upward, making a Y with the latter. Hence in the eroded section proximity of the original dike to its explosive parasite would depend upon the dip of the dike and the amount of erosion. A similar explanation can be applied to the formation of succeeding explosion tubes. Thus only in the case of vertical faults or joints would we find an explosion tube coinciding, in the eroded section, with the genetically asso-

ciated fracture. The relatively short duration of the igneous activity expressed in each of these small groups which seem to be genetically associated with faults and related dikes is possibly a function of the size of the parent-magma chamber. Had that been large, activity would have been more pronounced and longer lived (assuming the gases were primarily of juvenile origin), and what now is a cluster of explosive vents above a small intrusive mass might have been represented by a single igneous outcrop.

AUTHIGENIC EXPLOSION BRECCIAS (AUTOCLASTICS)

Mention has already been made of the variation in the proportions of the rock types composing the fragmental débris of the diatremes. If the foregoing explanation of the mechanism of formation is essentially correct, it is easy to see why the percentages of the different rock types should vary in the tubes. The kind of rock found in greatest abundance in any given pipe would be that of the particular geologic horizon at which the gas head was confined just prior to explosion. This might be the granite, the basal Lamotte sandstone, or any of the overlying carbonate series. Below the gas pocket the violence of the explosion would be dampened by the magma which occupied the tube. Above the confined gas column the rock would be largely blown out to the surface, some to fall back. To the small portion falling into the tube would be added a considerable amount that was torn from the walls by the inrush of air back into the hole. In much greater volume would be that fragmental material yielded by the shattering of the walls of the explosion chamber. This interpretation is suggested by field observation of brecciated aureoles around some of the tubes. The fragments of this breccia are almost identical lithologically and have undoubtedly been formed by the shattering of a single horizon. Movement of the broken rock was probably confined to a horizontal plane. Degree of fragmentation of this breccia varies rapidly with the distance from the contact. Figure 15 illustrates this variation as seen in a dolomite horizon.

A brief consideration of conditions just prior to explosion will suggest how such a breccia may have been formed. Surrounding the confined gas column would be an aureole of rock under the same gas pressure as that in the tube. The amount of gas in this rock would

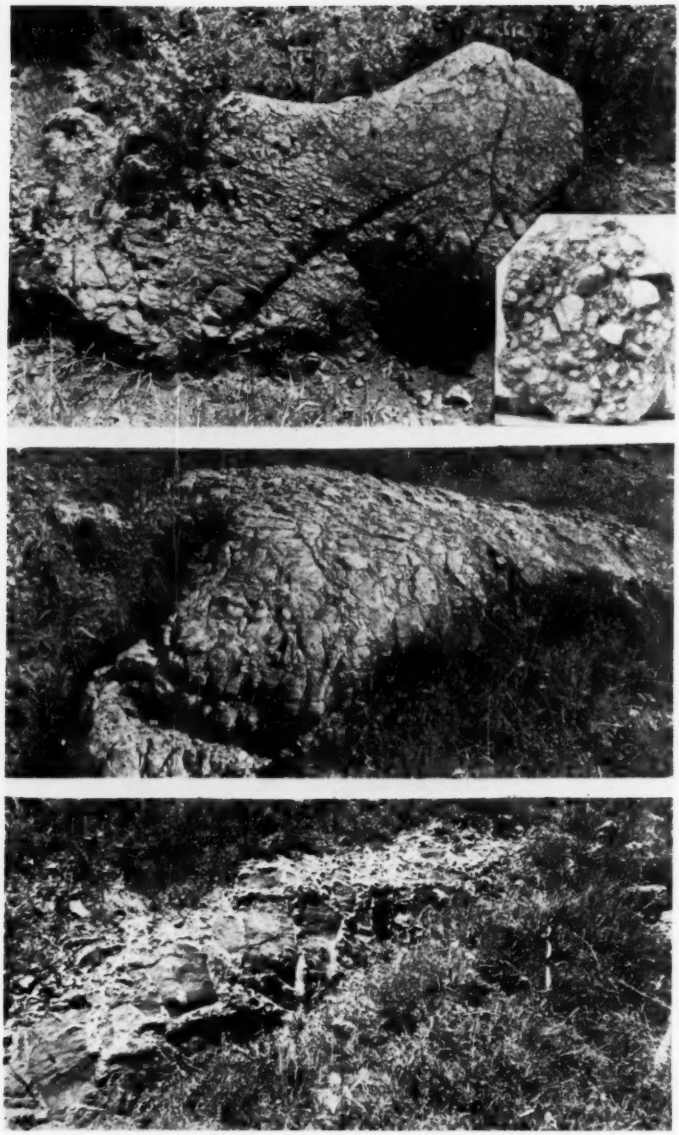


FIG. 15.—These photographs show the degree of fragmentation of dolomite ("authigenic explosion breccia") at 10 (above), 20 (center) and 100 feet (below) respectively from contact with diatreme. Note trace of bedding in lower part of center figure.

depend upon its porosity. At the culmination of the explosion the compression on the walls and that of the gas contained in the pores of the walls would be at a maximum. The forces would operate outward from the center of the tube. Following the explosion, the pressure in the tube would quickly drop to the atmospheric pressure or even less. Slightly after the explosion in the tube there would then be a counterexplosion of the confined gas in the pores of the wall rock, directed toward the center of the tube. This would cause shattering of the gas-bearing rock and projection of great quantities of it into the tube to mingle with infalling fragments and to be caught up by and incorporated within the rising lava column. The degree of shattering of the porous horizon would depend upon several factors, most important of which would be the temperature of the rock. This would diminish rapidly away from the contact and would be of no consequence below the boiling point of water.

The effectiveness and selectivity of this process is most surprising. In thin-bedded carbonate horizons highly brecciated beds 6 inches thick were observed underlain and overlain by bent but unbroken beds, also quite thin. If considerable solution had occurred within these selective horizons, brecciation might presumably have been aided somewhat by collapse. Collapse alone, however, would not account for the enormous amount of loose sand that found its way into some of the tubes and was incorporated in the magma column, resulting in a rock so rich in sand as almost to resemble a quartzite. It is easy to see that these "authigenic explosion breccias" might be mistaken for a rock of sedimentary origin.

POST-EXPLOSIVE ACTIVITY

Following the explosions the magma column rose and incorporated the débris in the tubes to various heights. Rapid cooling of this incorporating magma caused early solidification. Pressure continued from below, however, as evidenced by slickensiding of fractures. This movement was followed by filling of the fractures with calcite and small amounts of sulphides and oxides in some instances. Still later movements developed slickensiding in the vein fillings.

Alteration of the diatreme and dike rocks has reached an advanced stage. The change has been almost wholly one of hydrothermal car-

bonatization. This period of hydrothermal alteration and slight sulphide mineralization is believed to be an expression of the dying stages of igneous activity. There is a sharp and distinct difference between the results of this early metamorphism and recent surface alteration.

AGE

It is not easy to date this igneous activity geologically. One of the exposures has already been called post-Devonian in age by Tarr and Keller,[16] because Upper Devonian fossils were found in the limestone inclusions. Since we are not sure, however, that any rocks younger than Mississippian were ever deposited over the area, the fragmental material itself serves only to set a maximum age limit. Extreme alteration of the rocks makes the use of a radioactive method of age determination highly impractical. Any opinion must for the present be purely conjectural.

It may be noted, however, that the igneous activity in southern Illinois and Kentucky, which belong to the same general structural province, is definitely known to be post-Pennsylvanian in age. In Arkansas are occurrences of volcanic rocks which are definitely known to be of Upper Cretaceous age.[17] Miser and Ross, when describing the Arkansas volcanics, pointed out the similarity between these and the peridotite and lamprophyre rocks of Kentucky and Illinois and Riley County, Kansas,[18] and suggested the possibility that the igneous intrusions in the latter states also occurred in Cretaceous time. To this the writer wishes to subscribe, at the same time admitting ignorance of any significant evidence to support or disprove this belief.

ACKNOWLEDGMENTS.—Grateful acknowledgment is due the National Research Council and the Department of Geology at the University of Chicago for a grant-in-aid covering most of the field expenses. The writer is also indebted to members of the department for many helpful suggestions, particularly to Drs. Albert Johannsen and Francis J. Pettijohn.

[16] *Op. cit.*

[17] H. D. Miser and C. S. Ross, "Volcanic Rocks in the Upper Cretaceous of Southwestern Arkansas and Southeastern Oklahoma," *Amer. Jour. Sci.*, Vol. IX (Feb., 1925).

[18] R. C. Moore and W. P. Haynes, "An Outcrop of Basic Igneous Rock in Kansas," *A.A.P.G. Bull.*, Vol. IV (1920), pp. 183–87.

During the progress of the field studies it came to the writer's attention that Dr. Marvin Weller had spent the summer of 1923 in part of the above-described area of igneous activity. The writer communicated with Dr. Weller and found the latter had assembled considerable data on the peculiar rocks of the locality. This material, which proved of great value, was placed at the writer's disposal. Grateful acknowledgment is made to Dr. Weller for this important contribution.

The writer is grateful to the Illinois State Geological Survey for financing a short trip to the southern Illinois fluorspar district. Material and comparative data collected there have already proved useful in a general understanding of this type of volcanism and are expected to be of particular value in further studies on the petrology and hydrothermal alteration.

ORIGIN OF THE GREAT LAKES BASINS

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ABSTRACT

Attention is called to a growing tendency to overlook the hypothesis of glacial excavation as the primary cause of the Great Lakes. Alternate hypotheses, particularly diastrophism, are compared with the glacial hypothesis, and it is concluded that the evidence is much more favorable to glaciation. Points favoring glacial erosion include; the great depth of the basins; the finding of similar basins widespread over other glaciated areas; the absence of any evidence of recent diastrophism in the vicinity except that owing to isostatic recoil following deglaciation; the similarity of the basins to other features which are clearly the result of glaciation; and the thickness of the drift to the south of the Great Lakes.

INTRODUCTION

The time-honored hypothesis of glacial excavation as the principal cause of the Great Lakes basins appears to have fallen into disrepute. Most of the latest textbooks of geology and physiography either fail to mention a cause for these greatest of the world's fresh-water lakes or state merely that the basins are the product of land warping, glacial erosion, and glacial deposition. A number of writers have questioned the power of ice in continental glaciers to produce deep basins[1] and have given reasons for believing that other factors were more important. However, for one interested in the ice-erosion hypothesis the greatest surprise is to be found in a recent article regarding the bathymetry of Lake Michigan.[2] The writer of that paper boldly discussed the origin of the basin without even mentioning the possibility that glacial erosion might have been a factor. It is time that someone challenged this growing neglect of the glacial-erosion hypothesis before it reaches an undeserved state of senility. The present writer became interested in the problem through the study

[1] E.g., H. L. Fairchild, "Ice Erosion Theory a Fallacy," *Geol. Soc. Amer. Bull.*, *16* (1905), pp. 13–74; J. W. Spencer, "Origin of the Basins of the Great Lakes of America," *Amer. Geol.*, Vol. VII (1891), pp. 86–97; F. B. Taylor, "Study of Ice-Sheet Erosion and Deposition in the Region of the Great Lakes," *Geol. Soc. Amer. Bull.*, 22 (1911), p. 727; F. T. Thwaites, *Outline of Glacial Geology* (1st ed., 1927), pp. 42–44, (2d ed., 1934), p. 20. This excellent treatise on all phases of glaciation provided much information used in preparing the present article.

[2] O. F. Evans, "Bathymetric Studies of the Lake Michigan Basin," *Geog. Rev.*, Vol. XXV (1935), pp. 667–71.

of submarine topography and particularly through comparisons made of the bathymetry of the Great Lakes with that of the continental shelves and inlets in glaciated territory.

OBJECTIONS TO ICE EROSION

In regard to the Great Lakes the best statement of the objections to ice erosion is to be found in Thwaites' *Outline of Glacial Geology*.[3] He calls attention to islands of weak rock in the Lake Superior basin. He notes that the basins are too wide to be properly described as U-shaped, and he questions the existence of hanging valleys along the margins. Furthermore, he refers to similar basins which extend across the direction of ice movement and to neighboring basins in Wisconsin which are "explicable only as depressed parts of river valleys." He calls attention to the numerous glaciated surfaces where ice did not even remove the weathered material. Finally, he expresses doubts on theoretical grounds of the capacity of continental glaciers to erode deeply. The objections of other geologists are adequately covered by these same points.

ALTERNATE HYPOTHESIS

That glacial deposition blocking the outlet of preglacial depressions is the principal cause of the lakes has been suggested. Spencer[4] believed that the basins were cut below present sea-level by streams as a result of uplift prior to the glacial period. Attention has also been called by Thwaites and others to the warping in the Great Lakes region which might suggest a diastrophic origin. Other deep basins, such as the Rift Valley lakes of Africa, the large lakes of Asia, and the basins of Nevada and Utah have been caused by diastrophism.

TESTS OF THE HYPOTHESES

Though it is recognized that in all probability several factors have contributed to the development of the Great Lakes basins, the question arises whether some one of them has not been of major importance. Tests may be applied which should make a decision on this point possible.

Drift-obstructed preglacial valleys.—In the first place, if the basins

[3] *Op. cit.* The first edition contains a more complete statement, although the second edition is more moderate in its condemnation of glacial erosion.

[4] *Op. cit.*, p. 94.

are largely drift-obstructed valleys, cut originally by river erosion, the bottoms of the basins should be higher than the rock floors of the seaward extension of these old valleys. Also, the basins should show cross sections of a character suggestive of river erosion and in keeping with the relation of the valleys to the drainage divide.

These expectations are not fulfilled. It is well known that all the Great Lakes except Lake Erie extend below sea-level (for maximum depths see Fig. 1), and their rock bottoms may be at a much greater depth than shown by the soundings because the retreat of the ice may have left considerable drift coverings in these basins. Thwaites notes that "well records fail to show any wide preglacial valleys leading out of the basins of the Great Lakes," and ". . . . the rock bottoms of the Mississippi and other preglacial valleys are much higher than the bottoms of the Great Lakes."[5] In order to assume some gradient toward the Mississippi, which was probably the preglacial outlet of the Great Lakes drainage basin, the bottoms of the preglacial valleys must have been almost as high as the present surface of the Great Lakes. Furthermore, the area in question, being so centrally located, must have been close to the drainage divide. It is hard to conceive of river valleys in such a location with floors as wide as those of the Great Lakes basins (Fig. 2). Nor do the outlines of the basins have the typical sinuous outlines of river valleys. Under the circumstances it seems unwise to attribute the present deep basins of the lakes to preglacial river erosion although the probability that small river-valley depressions existed along the lines of the Great Lakes must be recognized. As a corollary, glacial deposition must be relegated to the unimportant rôle of helping to limit the size of basins formed in other ways.

Similar basins in glaciated regions in general.—A second test may be made of the relative merits of the hypotheses of glacial erosion and diastrophism. If the basins were due to glaciation, similar basins might be found widespread over the glaciated territories of the world; whereas, if they are diastrophic, such a wide distribution in glaciated regions would be most unlikely. In considering this criterion three things must be borne in mind: first, that some of the basins do not appear as lakes because they are completely submerged by the ocean; second, that the basins in areas glaciated in early

[5] *Op. cit.* (1st ed.), p. 43.

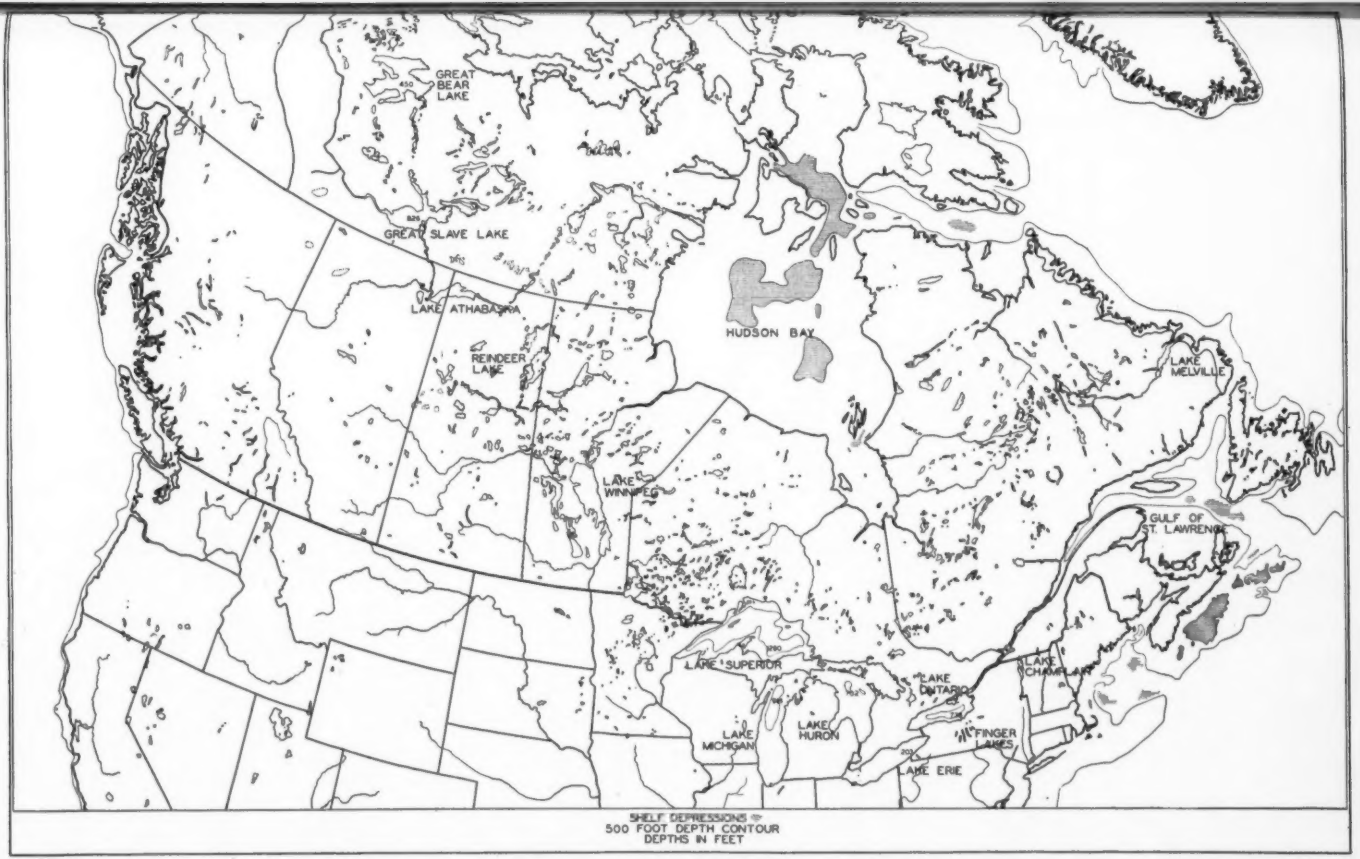

FIG. 1.—Showing the basins associated with glaciation in North America. Depths are in feet. The principal basins on the continental shelves are shaded

epochs would have been filled to a considerable extent; and, third, that the greatest gouging action of the ice would be expected around or close to the margins of ice sheets, so that the absence of basins in the interior would not be significant. With these points in mind we may proceed to an examination of the principal glaciated territories.

A map of North America (Fig. 1) shows a series of large lakes occupying basins in the soft rocks on the south and west borders of the Canadian shield, and bathymetric maps show that a lowering of sea-level would leave similar lake basins in the gulfs and bays southeast and north of the shield. The Great Lakes basins are neither the largest nor the deepest of these features. The Finger Lakes of New York State and Lake Champlain are smaller than, but almost as

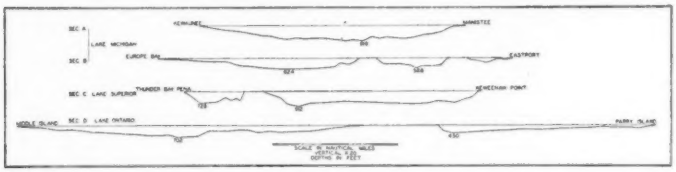

FIG. 2.—Cross sections of the Great Lakes. Note the relatively steep sides and broad base.

deep as, the Great Lakes. The Gulf of St. Lawrence is comparable to the Great Lakes and contains large, deep, rimmed depressions.[6] Along the coast to Labrador a few inlets, notably Lake Melville, are also comparable, but in general the inlets or fiords are too small to warrant consideration.

North of Canada the series of straits and gulfs among the islands have been charted only very crudely, and soundings are scarce. Such information as is available, however, suggests that these bodies of water are similar to the Gulf of St. Lawrence and probably contain basins of a depth and size quite comparable to the Great Lakes. Hudson Bay has been sounded sufficiently to show that it has basins within it which compare in dimensions with the Great Lakes. Great Bear Lake, Great Slave Lake, Lake Athabasca, Reindeer Lake, and Lake Winnipeg are almost as large as the Great Lakes. Their depths are not well known, but soundings in Great Slave Lake show a max-

[6] F. P. Shepard, "The St. Lawrence (Cabot Strait) Submarine Trough," *Geol. Soc. Amer. Bull.*, *42* (1931), pp. 853–64; see also Fig. 6, p. 860.

imum of 826 feet and in Great Bear Lake of 450 feet[7]—depths not unlike those of the Great Lakes. On the other hand, Lake Winnipeg does not have depths much in excess of 60 feet so far as is known.

In the European glaciated area (Fig. 3) there are various large lakes, and the seas and gulfs contain many basin depressions. The Skager Rack, south of Norway, has a deep, rimmed basin.[8] The Baltic Sea, the Gulf of Bothnia, and the Gulf of Finland all contain sizable depressions. Farther east in the Soviet Union are Lake Ladoga and Lake Onega. The White Sea contains a deep basin, and the continental shelf in the Barents Sea contains a series of deep, rimmed depressions.

All these examples of large basins in glaciated regions of relatively low relief show that the Great Lakes are features characteristic of continental glaciation. The areas immediately outside the glaciated regions, together with much of the area of marginal glaciated territory, where the glaciers were thin and of short duration, have few basins both on the lands and on the continental shelves. Accordingly, it appears that the Great Lakes are in some way related to glaciation.

Diastrophism in glaciated territory.—The possibility must be considered that the abundance of basins in the glaciated territory simply means that this territory has also been very active diastrophically. Tests will be applied to see whether this is the case. First, let us consider the earthquake distribution in relation to glacial territory. If we place the great seismic belts and the glaciated territory on the same world-map, we find that the two hardly coincide at all (Fig. 4). Further consideration shows that both the Scandinavian center in Europe and the Labradorian and Keewatin centers in America are related closely to ancient shields where stability has long been developed. Nor are there notable fault scarps and fault troughs developed in these regions.

Now, if we consider the other areas of the world which contain large basins, we find a very different picture. These areas are found within earthquake belts in practically every case. The areas con-

[7] From information kindly supplied by F. Anderson, hydrographer, Canadian Hydrographic Service.

[8] F. P. Shepard, "Glacial Troughs of the Continental Shelves," *Jour. Geol.*, Vol. XXXIX (1931), Fig. 9, p. 352.

BARENTS SEA
WHITE SEA
GULF OF BOTHNIA
LAKE ONEGA
LAKE LADOGA
GULF OF FINLAND
SKAGER RACK
BALTIC SEA

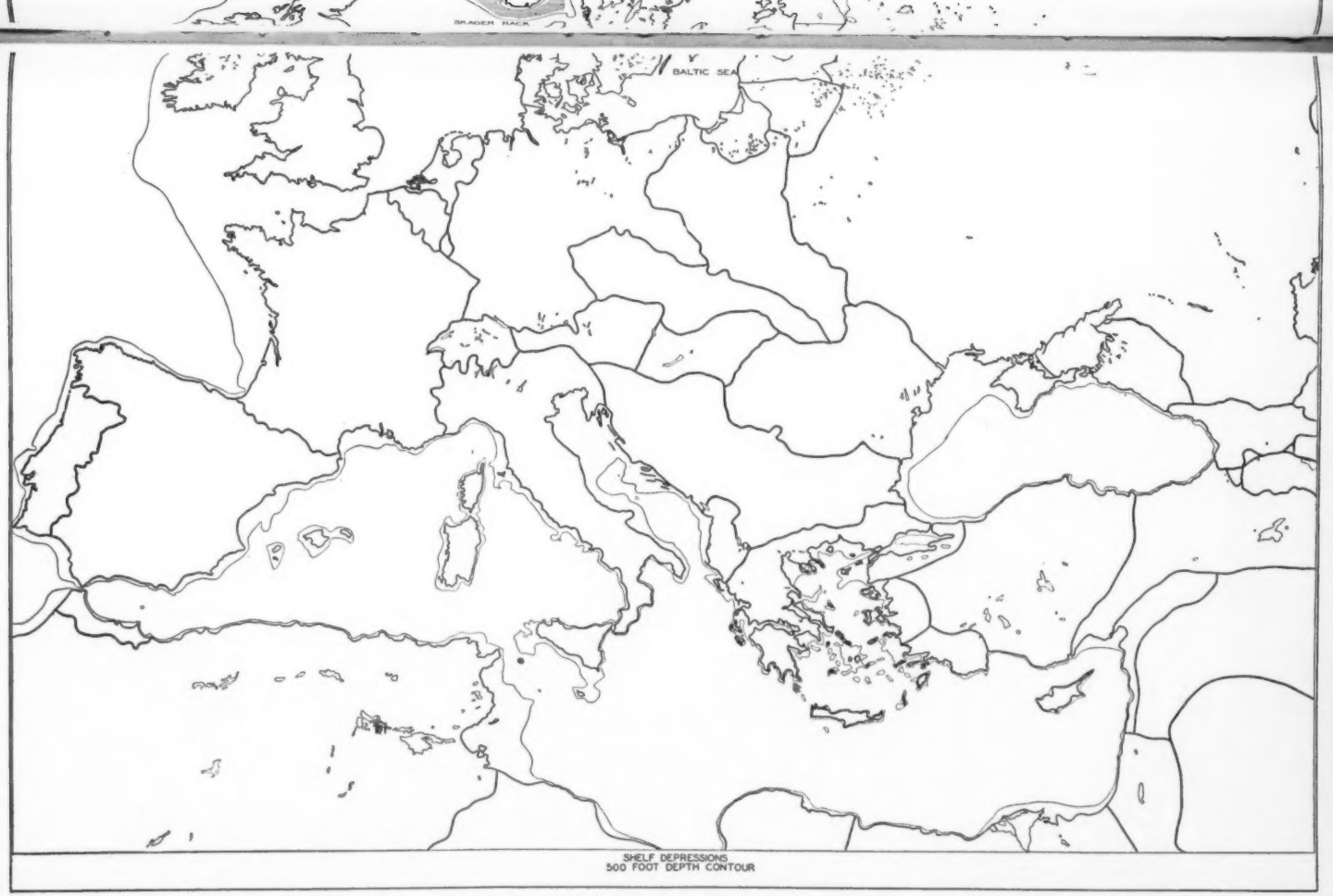

FIG. 3.—Showing the basins associated with glaciation in Northern Europe. Basins on the continental shelves are shaded

tain a maze of fault scarps and all other indications of having been active diastrophically in recent times.

The argument that there has been warping in glaciated territory in postglacial times requires some consideration since this may represent the cause of the basins. It is generally agreed, however, that this warping is the result of readjustment of the earth's crust following the release of the load of the continental glaciers. The compilation of the data by Gutenberg[9] shows that, so far as the Great Lakes area is concerned, there is a progressive rise from the southern

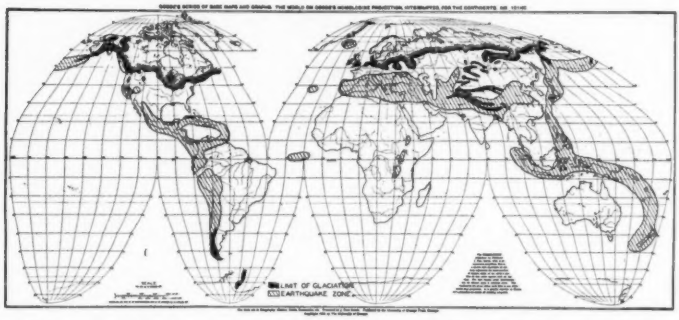

FIG. 4.—Showing the lack of relation between earthquake belts and glaciated territory.

boundary of the lakes to the north. The principal effect of such a tilt would be to decrease the size of the basins, and it certainly should not be considered as an important factor in their production.

MOVEMENT OF THE ICE

The various opponents of the idea that ice excavation is important have made much of the presence of deep basins transverse to the general motion of ice. This is true of many of the fiords along the various glaciated coasts of the world. It does not, however, disprove the glacial-excavation hypothesis. It is well known that in areas of continental glaciation numerous glacial striations cross the general direction of ice flow. Also, as has been pointed out by Bretz,[10] the present continental glacier of Greenland has a concen-

[9] B. Gutenberg, "Tilting Due to Glacial Melting," *Jour. Geol.*, Vol. XLI (1933), p. 458, Fig. 3.

[10] J H. Bretz, "The Fiord Region of East Greenland, "*Geog. Soc. Spec. Publ. 18* (1935), p. 239.

trated flow along the fiords which are buried beneath the ice of the interior. This observation helps explain why there is such clear evidence of excavation along certain valleys in formerly glaciated regions whereas the uplands between the same valleys were not subject to much glacial erosion.

That the ice did move down the Great Lakes basins is clearly indicated. The map compiled by Leverett[11] shows the various lobes of ice which occupied each of the basins. These lobes have been demonstrated by the glacial striations and by the morainic belts which surround the outer termini of the Great Lakes basins.

COMPARISON WITH FIORDS AND OTHER GLACIAL FEATURES

It is quite generally conceded that fiords are due largely to glacial erosion. Also, the large lakes of Switzerland and other glaciated mountain ranges are certainly glacial excavations.[12] The writer called attention to the complete gradation which exists between fiords and submarine troughs out on the open continental shelves off glaciated coasts.[13] The Great Lakes, likewise, can be shown to be related to the mountain lakes of Switzerland with all gradations between the two. All four of these features have many points in common. Thus, while the Great Lakes are not strictly U-shaped, their transverse profiles are trough shaped with relatively steep walls on either side (Fig. 2). Also, the sides of the lakes are comparatively straight as are the sides of many glacial valleys in the mountains and the fiords of glaciated coasts. The unconnected depressions which characterize Lake Superior (Fig. 5) have their counterpart in most fiords and in many large mountain lakes. The rocky islands within Lake Superior, which were cited by Thwaites as an argument against ice erosion, are matched by the rocky islands of most fiords and are found also in some of the Swiss lakes.

In 1870 Andrews[14] called attention to certain subaqueous terraces

[11] F. Leverett and F. B. Taylor, "The Pleistocene of Indiana and Michigan," *U.S. Geol. Surv. Mono. 53*, Pl. V, opp. p. 62.

[12] The attempts which have been made to explain fiords and mountain lakes as diastrophic are not characterized by the clear reasoning which scientific arguments should have. This point is well developed by D. W. Johnson, "The Origin of Fiords," *Science*, N. S., Vol. XLI (1916), pp. 537–43.

[13] F. P. Shepard, "Glacial Trough of the Continental Shelves," *Jour. Geol.*, Vol. XXXIX (1931), pp. 347–57.

[14] Edmund Andrews "The North American Lakes Considered as Chronometers of Post Glacial Time," *Chicago Acad. Sci. Trans.*, Vol. II (1870), pp. 1–23.

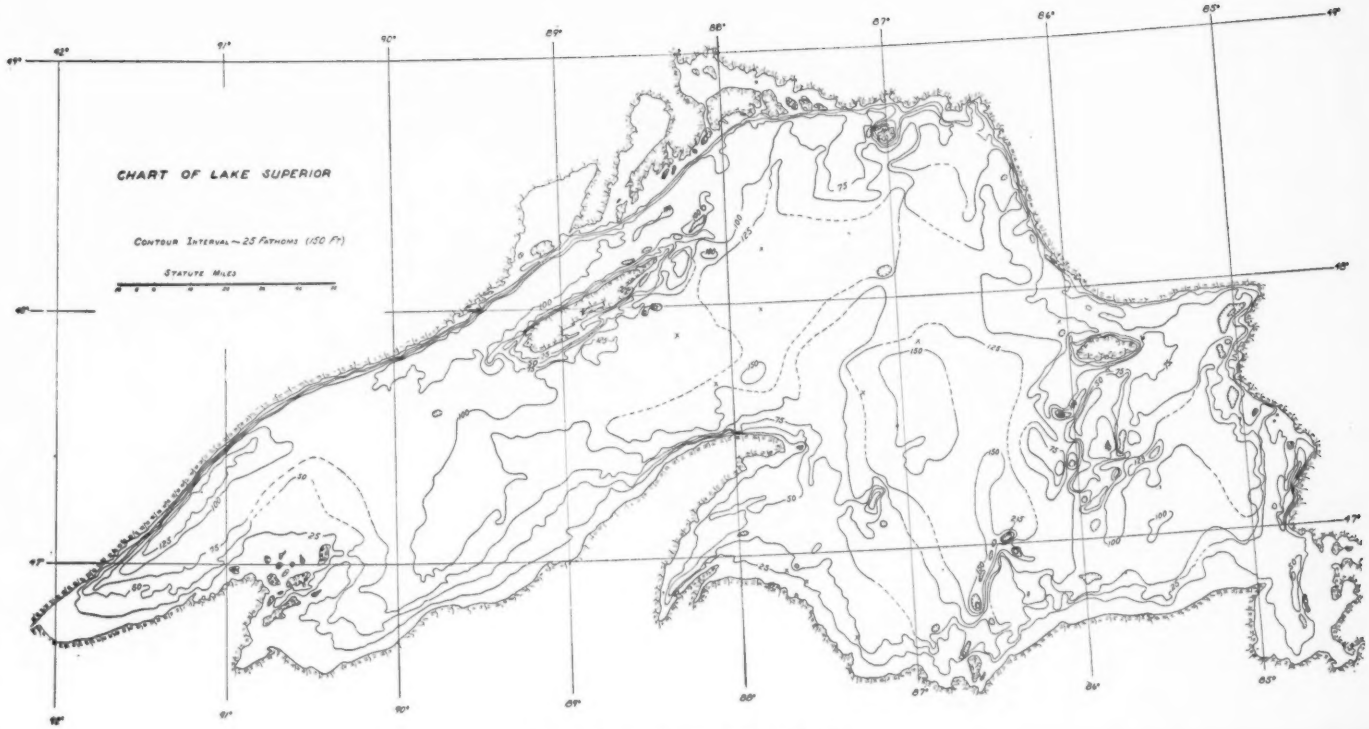

FIG. 5.—Contour map of Lake Superior

along the margin of Lake Michigan which he thought extended to depths of 60 feet. Johnson[15] subsequently examined the evidence for these terraces and concluded with good reason that the soundings did not permit any such generalization as Andrews had made. He suggested that the terraces and valleys on the lake floor at some places were submerged land features. However, some of these valleys cited

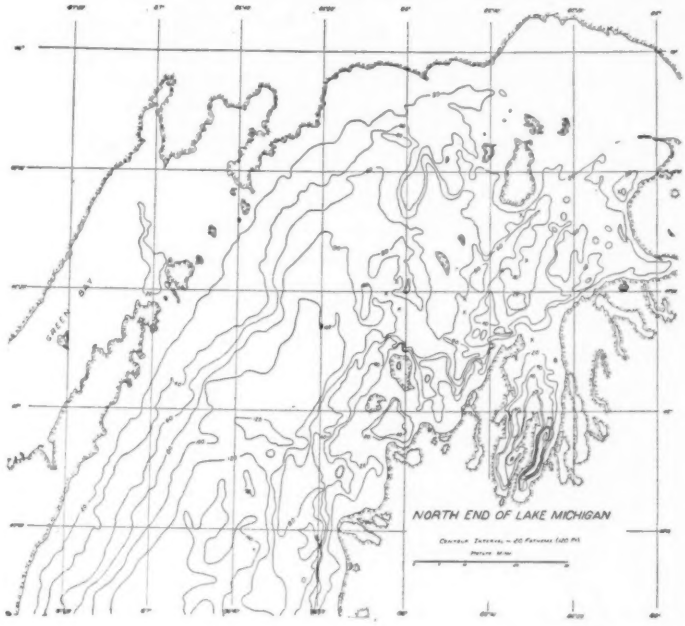

Fig. 6.—Contour map of the northern portion of Lake Michigan

have been shown by the recent surveys to contain deep, rimmed depressions so that they can hardly be ascribed to river erosion, and near them are similar features more than 600 feet deep (Fig. 6, lower left corner). Is it not more reasonable to assume that these features were produced by glacial erosion, especially as some of the submerged valleys have distinct U-shaped transverse profiles?

The irregular topography of the lake bottoms, expecially that of

[15] D. W. Johnson, *New England-Acadian Shoreline* (New York: John Wiley & Sons, 1925), pp. 405–15, 28.

Lake Superior, suggests that it has not been greatly modified by postglacial deposition. The "rock bottom"[16] reported in surveys from various parts of the lake floors and glacial till reported from Lake Michigan[17] and from Lake Erie[18] corroborate this conclusion.

THICKNESS OF GLACIAL DRIFT

One of the most convincing arguments favorable to glacial excavation of the Great Lakes is the enormous quantity of glacial drift found south of these basins. Despite postglacial erosion and the fact that a large percentage of the débris was carried beyond the glacial margins by glacial outwash, the surfaces are, nevertheless, covered with drift which is commonly a hundred or even several hundred feet in thickness. Furthermore, the nature of the drift is such as to suggest derivation from adjacent lake basins as, for example, the clayey till of Illinois which was presumably derived from the shales of the Lake Michigan basin. The freshness of a large part of the drift, particularly the younger sheets, shows conclusively that the glaciers were digging into solid rock rather than just removing the mantle rock from old weathered surfaces.

CONCLUSIONS

The various tests which have been applied to the hypotheses of origin of the Great Lakes appear to give overwhelming weight to glacial erosion as the principal cause. Possibly such a conclusion is not justified, but more significant evidence should be given before assuming alternative modes of origin. If it is true that the Great Lakes, the various other large basins in glaciated territory, and the deep arms of the ocean along glaciated coasts are all largely the product of glacial erosion, one is led to wonder whether the glaciers were not much thicker than commonly assumed. An average thickness of 4 miles or more for the continental ice masses has been suggested by the writer as a cause of great lowering of sea-level to permit the cutting of submarine canyons. If the ice was that thick, the cutting of large basins might have been greatly intensified.

[16] These may be largely boulders rather than bedrock.

[17] J. L. Hough, "The Bottom Deposits of Southern Lake Michigan," *Jour. Sed. Pet.*, Vol. V (1935), pp. 57–80.

[18] E. M. Kindle, personal communication.

CROSS-BEDDING AND FORMATION THICKNESS DETERMINATIONS

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ABSTRACT

When cross-bedding is mistaken for normal bedding and its attitude used in the calculation of formation thickness, an error will result, the magnitude of which depends upon the angle between the normal bedding and the surface of outcrop as well as upon the angle between the normal bedding and the cross-bedding. The effect of the former angle upon formation thicknesses so calculated is discussed for several sets of conditions.

It is a matter of common knowledge to geologists that the determination of thickness of a cross-bedded formation will be incorrect if the dip of the cross-bedding is used in making the calculation instead of the dip of the normal or main formation bedding. It does not seem to be generally recognized, however, that the extent of the error depends not only upon the angle between the cross-bedding and the normal bedding but also upon the angular relation between the normal bedding and the surface at which the data for formation measurements are obtained—i.e., the surface of outcrop. Some recognition of this fact may be implied in the following statement by Lahee, though the statement speaks only of structural interpretation:

> In studying outcrops of strata with the purpose of determining the dip, great care must be exercised lest cross-bedding be mistaken for true bedding. This confusion is less apt to occur in steeply dipping strata than in gently dipping strata, and the relative error in the resulting structural interpretation is generally less in the former than in the latter.[1]

Nowhere has the writer seen any comprehensive discussion of this matter. The purpose of this paper is to discuss the manner in which this angular relationship affects thickness determinations where cross-bedding is mistaken for normal bedding.

The possibility of introducing a serious error into thickness calculations by mistaking cross-bedding for normal bedding is par-

[1] F. H. Lahee, *Field Geology* (3d ed.; New York: McGraw-Hill Book Co., 1931), p. 383.

ticularly great in the case of sandstones which were deposited as the foreset beds of deltas. The cross-bedding may be the only bedding visible in outcrops over extensive areas and dip observations may be generally consistent, as would be expected in the subaqueous counterpart of a compound alluvial fan. In such instances only the broader relationships would indicate the attitude of the normal bedding.

For convenience in the following discussion, horizontal surfaces of outcrop are assumed. The principles involved are the same, whether the surface is horizontal or sloping. The general statement of the problem is that the error introduced into a thickness calculation by using cross-bedding instead of normal bedding is primarily a function of the two angles involved, namely, (1) the angle between the cross-bedding and the normal bedding and (2) the angle between the normal bedding and the surface of outcrop. It is recognized, of course, that the surface of outcrop may be either rough or smooth. The average inclination from one edge of the outcrop to the other, taken in the direction of dip, is what counts. Moreover, for purposes of discussion, it is assumed that the strike of the cross-bedding is in essential agreement with the strike of the normal bedding. There will be many instances, of course, where the strike is not virtually the same for the two types of bedding. This condition introduces further complications, the possible range of which is very extensive.

In calculations of formation thickness the connection between the amount of error which would result from observations on cross-bedding and the angular relationship between the formation dip and the surface of outcrop is readily illustrated by two simple cases which differ only in this angular relationship. Two such cases are shown in Figures 1 and 2, the diagrams representing vertical sections at right angles to the strike of the bedding. In each the cross-bedding is steeper than the normal bedding, the dip of both is in the same direction, and the angle between them is the same, namely 25°, which is not far from the maximum angle possible for subaqueous deposits of sand. In one case the formation dip is 10° and the dip of the cross-bedding 35°. In the other case the formation dip is 55° and the dip of the cross-bedding 80°.

From these illustrations it is readily seen that the apparent thickness A, based upon cross-bedding, is greatly in excess of the true

thickness T where the angle α between the normal bedding and the surface of outcrop is small, but it is only slightly in excess of the true thickness where this angle is large.

The reason for the difference lies in the overlapping or shingle effect resulting from the cross-bedding. In the case of the small angle between the normal bedding and the surface of outcrop many more units or "shingles" are exposed than would actually be found on a surface at right angles to the normal bedding of the formation; and these additional units, entering into the thickness determination, give a large apparent thickness. In the case of the large angle be-

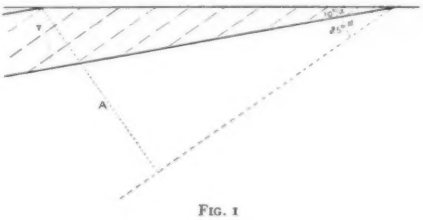

FIG. 1

FIG. 2

FIG. 1.—Cross-bedding dipping steeper than normal bedding and in same direction; dip of normal bedding gentle.

FIG. 2.—Cross-bedding dipping steeper than normal bedding and in same direction; dip of normal bedding steep.

tween the normal bedding and the surface of outcrop very few more units or "shingles" are exposed than would be found on a surface at right angles to the normal bedding, thereby giving a thickness determination only slightly greater than the true thickness.

In general terms the relationship between apparent thickness and true thickness under the above conditions may be expressed by the formula

$$A = T \frac{\sin (\alpha+\beta)}{\sin \alpha},$$

where β represents the angle between the normal bedding and the cross-bedding, and the other symbols represent the items previously indicated. For a given thickness of formation (T constant) the denominator of the fraction increases more rapidly than the numerator as the angle α increases and the apparent thickness therefore decreases.

Applying the formula to the two cases illustrated in Figures 1 and 2 and assuming a true thickness of 100 feet, the apparent thickness in the former case is found to be 330 feet, or an excess of 230 per cent over the real thickness, whereas in the latter the apparent thickness is 120 feet, or an excess of only 20 per cent.

If, however, the cross-bedding is gentler than the normal bedding and both dip in the same direction, fewer units or "shingles" are exposed than would be found on a surface at right angles to the normal bedding. Under these conditions the smaller the angle between the normal bedding and the surface of outcrop, the smaller the number

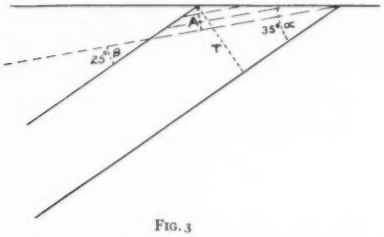

FIG. 3

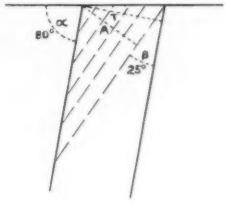

FIG. 4

FIG. 3.—Normal bedding dipping steeper than cross-bedding and in same direction; dip of cross-bedding gentle.

FIG. 4.—Normal bedding dipping steeper than cross-bedding and in same direction; dip of cross-bedding steep.

of "shingles" exposed and the greater the discrepancy between apparent thickness and true thickness.

Figures 3 and 4 illustrate two cases in which the dip of the cross-bedding is gentler by 25° than the dip of the normal bedding and in the same direction. The normal bedding in one case dips 35° and in the other case 80°. The relationship between apparent and true thickness under the condition illustrated in these two cases may be expressed by the formula

$$A = T \frac{\sin (\alpha - \beta)}{\sin \alpha} .$$

Applying this formula to these two cases, again with an assumed thickness of 100 feet, the apparent thickness is found to be 30.3 feet for the condition illustrated in Figure 3 and 83.2 feet for that illustrated in Figure 4.

Attention is called again to the fact that, in the illustrations given, the strike of the normal bedding and the strike of the cross-bedding are assumed to be mutually parallel, the planes of both being at right angles to the plane of the section in each case. There are two other general possibilities to consider, assuming parallelism of strike. When

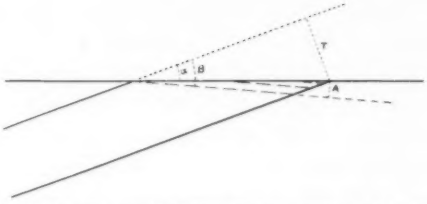

FIG. 5.—Normal bedding and cross-bedding dipping gently and in opposite directions

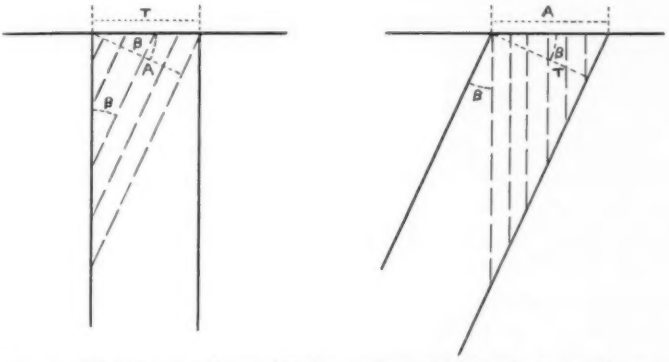

FIG. 6.—Limiting cases of normal bedding and cross-bedding dipping steeply and in opposite directions; left, dip of normal bedding vertical; right, dip of cross-bedding vertical.

the cross-bedding and the normal bedding dip in opposite directions, the dip of both, in the nature of the case, must be either fairly gentle or very steep since the angle between cross-bedding and normal bedding in water-laid sediments is rarely more than 25°. Figures 5 and 6 illustrate these two conditions.

In the case of the gentle dip (Fig. 5), apparent thickness can range from a minimum theoretically nil, when cross-bedding is parallel to

the surface of outcrop, to a maximum, amounting to the product of the extent of the formation transverse to the strike of the cross-bedding on the erosion surface and the sine of the angle of cross-bedding, when normal bedding is parallel to the surface of outcrop. The limiting case giving the minimum apparent thickness will be recognized as a limiting case also for the conditions illustrated in Figure 3, whereas the limiting case giving the maximum apparent thickness is a limiting case also for the conditions illustrated in Figure 1.

In the case of the steep dip, apparent thickness cannot differ very greatly from true thickness. It ranges from a minimum when the normal bedding is at right angles to the erosion surface (Fig. 6*a*), in which case it amounts to the true thickness times the cosine of the angle of cross-bedding, to a maximum when the cross-bedding is at right angles to the erosion surface (Fig. 6*b*), in which case it amounts to the true thickness divided by the cosine of the angle of cross-bedding. The former will be recognized as a limiting case for the conditions illustrated in Figure 4 and the latter as a limiting case for the conditions illustrated in Figure 2.

From the above discussion it is readily seen that the amount of error liable to result in the determination of thickness of a cross-bedded formation generally increases as the angle between the dip of the normal bedding and the erosion surface decreases, the only exceptions occurring where the dips of the cross-bedding and the normal bedding are in opposite directions, and then only in parts of the range of possible conditions. Such error may conceivably become so great as to lead to incorrect conclusions of serious import, not only as to depth to one or more horizons of economic importance, as in exploration for coal or oil, but also in structural interpretation, even in extreme cases to the point of mapping a flexure which does not exist.

ACKNOWLEDGMENTS.—The writer is indebted to Professors A. N. Winchell and Rollin T. Chamberlin for critical reading of this paper and for helpful suggestions.

A MOUNTED SKELETON OF *LABIDOSAURUS* COPE

EVERETT CLAIRE OLSON
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ABSTRACT

A recently mounted skeleton of *Labidosaurus* is figured and described. Inferences drawn from the skeleton indicate that this animal was a heavily muscled form with certain specializations not known in other North American cotylosaurs. A brief discussion of the habits of the animal is presented.

INTRODUCTION

During the last forty years many specimens of *Labidosaurus* have been collected from the Clear Fork Permian beds of Texas. Although the osteology of this cotylosaur has been worked out in considerable detail from a study of these specimens, only one skeleton found heretofore has been sufficiently perfect and workable to permit the preparation of a free mount.[1] Much of the skeletal material of *Labidosaurus* came into the able hands of Williston at the Walker Museum of Paleontology, the University of Chicago. In 1917, on the basis of a number of specimens imbedded in hard, ironstone nodules, Williston[2] made a restoration of the skeleton of *Labidosaurus*. In the light of new data he corrected certain errors existing in an earlier restoration by Broili. Very little additional information concerning this genus has been published since 1917.

The specimen of *Labidosaurus* under consideration in the present paper (University of Chicago, No. 1543) was collected by Mr. Paul C. Miller from the Clear Fork Permian beds north of Seymour, Texas, in 1928. It was worked out of the block and partially prepared for mounting by the writer in 1933. Recently Mr. Miller has completed the task of preparation and has made a free mount of the specimen.

DESCRIPTION

General.—The skeleton, although somewhat flattened, was articulated back to the twenty-third presacral vertebra when found. The

[1] In the Munich collections.

[2] S. W. Williston, "*Labidosaurus* Cope, a Lower Permian Cotylosaur from Texas," *Contr. from Walker Museum*, Vol. II (1917), pp. 45–57.

skull, 23 vertebrae, ribs, shoulder girdle, forelimbs, and left front foot were in place. Only the foot and ribs were appreciably damaged. Associated with the skeleton, but not articulated, were both femora, a right tibia, left fibula, the pelvic girdle, the sacral vertebrae and ribs, and 4 caudal vertebrae.

In mounting the skeleton, the missing parts were restored on the basis of other specimens in Walker Museum. A skull of an animal of the same size has been substituted for that belonging to the mounted skeleton, because the original skull, although complete, was badly crushed.

The total length of the mounted skeleton is 40 inches, but the actual length of the tail is uncertain, since no *Labidosaurus* with a com-

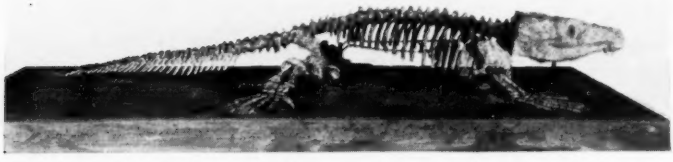

FIG. 1.—Mounted skeleton of *Labidosaurus* Cope, left side. About $\frac{1}{10}$ natural size. (University of Chicago, No. 1543.)

plete tail has ever been found. The length of the presacral column is 13 inches; and that of the skull, 7 inches. The specimen is somewhat larger than the average *Labidosaurus*.

Axial skeleton.—There are 25 presacral vertebrae; and, except for the atlas and axis, these are but little differentiated. The most striking feature of the column is the small size of the atlas and axis in relation to the size of the skull. The articulation of the occipital condyle with the spinal column was weak. The neural arches of the vertebrae increase in width from the axis to the sacrum, while the transverse processes diminish in size and seem to be absent on the last three or four presacral vertebrae. The neural spines increase slightly in size from the third presacral vertebra to the sacrum. Although the two sacral vertebrae are strong, they are not fused together. The tail, as restored, is about 20 inches long and contains 35 vertebrae.

Ribs occur on all but the last three or four presacral vertebrae and are well developed on the atlas and axis. Ribs 3–6 have very broad distal ends, apparently associated with the support of the scapulae. The two sacral ribs, which are fused to the sacral vertebrae, are expanded distally to articulate strongly with the ilium. Small fixed ribs appear to have been present on the first four or five caudal vertebrae.

The vertebral column in the trunk region of the specimen mounted in Munich has a ventrad curvature. As Williston has pointed out,[3] such a restoration is quite certainly in error. The articulations between the vertebrae of the recently mounted skeleton, as well as those of several other specimens, do not permit the column to assume such a position. Functionally the vertebral column serves to support the trunk region against vertical forces; and to do this effectively it must possess a slight arch, especially in *Labidosaurus* and similar forms in which the interspinal muscles seem to have been small and weak.

Girdles.—Both the pectoral and pelvic girdles are in good condition and essentially complete. The pectoral girdle was found immediately back of the skull, presumably in its natural position. The scapulae and clavicles were somewhat flattened and thus do not extend quite so far dorsally in the mount as they probably did in the living animal.

The pelvic girdle is essentially complete, although it was not articulated with the skeleton and had been broken into several pieces. Sutures between the three elements are not visible. The most interesting member of the innominate series is the ilium, which shows a distinct advance over the ilia of the contemporary cotylosaur *Diadectes*.[4] In the latter the ilium possesses a dorsal shelf over which the long lateral axial muscles appear to have passed. This condition represents a stage which is somewhat advanced over that found in the Permo-Carboniferous amphibian *Eryops*, in which the muscles seem to have passed along the outer surface of the iliac blade.[5] In *Labidosaurus* there is every indication that all the long axial muscles

[3] *Ibid.*

[4] A. S. Romer, "The Locomotor Apparatus of Certain Primitive and Mammal-like Reptiles," *Bull. Amer. Mus. Nat. Hist.*, Vol. XLVI (1922), pp. 517–606.

[5] *Ibid.*

lay medial to the blade of the ilium and that the ilium had grown dorsally to isolate these muscles from its lateral surface. There seems to have been a corresponding enlargement of the ilio-femoralis, as indicated by the muscle scars on the femur and the absence of any line marking the dorsal boundary of the muscle on the ilium.

Limbs.—The left forelimb is complete except for the phalanges of the foot, which were partially destroyed. The right forelimb is complete except for the foot. The screw-shaped glenoid fossa and the head of the humerus are so constructed that it probably was impossible for the animal to bring the humerus below the horizontal. The distal end of the humerus seems to have been carried somewhat higher than the head. The ulna is relatively heavier than Williston indicated in his descriptions, and the olecranon process is very well developed. The nature of the articulation of the radius and ulna with the humerus must have made it difficult for the animal to turn its front feet forward, and they probably were directed laterally, as they are in the mount.

The hind limbs are not so complete as the front; but both femora, the left tibia, and the right fibula are preserved. The hind limbs seem to have extended out to the side in much the same manner as the front; likewise the femur probably could not have been lowered much below the horizontal. The hind feet have been completely restored from Williston's illustrations. The main movement of the hind limbs appears to have resulted from a rotation of the femur by the contraction of the strong coccygeo-femoralis and pubo-ischio-femoralis internus muscles.

DISCUSSION

General.—There are several interesting points to be noted in the mounted skeleton which are not apparent in the individual bones or unassembled skeletons. *Labidosaurus* was a larger and more robust animal than would appear from the unmounted bones. The skull is large in proportion to the body, but its articulation with the vertebral column is weak. The animal had a sprawling posture, with the limbs projecting out to the side and the fore and hind feet directed laterally.

Myology.—Certain inferences concerning the musculature of *Labidosaurus* may be drawn from the mounted specimen, although it is

impossible to restore the complete musculature because of the small size of the animal and the inadequate preservation of certain bones.

The medial axial muscles, spinalis dorsi, and semi-spinalis dorsi, appear to have been rather weak. Their vertical extent was slight, as indicated by the very short neural spines; but their width was considerable since they presumably extended out to the margins of the broad neural arches. There is no indication on the vertebrae that these muscles were excessively tendinous to compensate for their small size. The lateral axial muscles, longissimus dorsi and ilio-

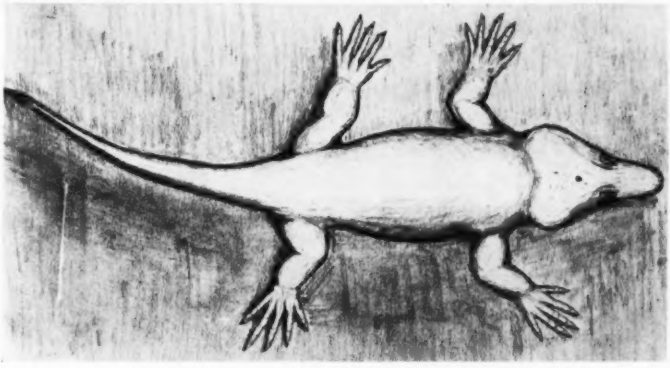

FIG. 2.—Restoration of *Labidosaurus* based on mounted skeleton. About $\frac{1}{4}$ natural size.

costalis dorsi, appear to have been strongly developed. That they had strong insertions on the ribs is indicated by the prominent dorsal crests on the shafts of all the well-preserved ribs. There were undoubtedly strong tendons passing from the ilio-costalis dorsi to the dorsal margins of the ribs, but it is impossible to tell with certainty whether or not these tendons passed through the muscle to give it a metameric appearance. All of the axial muscles seem to have passed inside of the dorsal extension of the iliac blade.

The cervical muscle must have been strong since the skull is large and massive. However, the small size of the axis indicates that the muscles from this bone to the occipital region of the skull were small and weak. These muscles function to produce lateral movements of the skull. In contrast to the weak occipital muscles, the cervical extensions of the dorsal axial muscles, particularly the lateral mem-

bers, appear to have been strong. The principal function of these muscles is to raise the skull, but they also aid in moving it laterally and ventrally. It may be concluded that the major movement of the skull was vertical and that it moved to some degree in unison with the anterior part of the vertebral column.

As already indicated, the musculature of the limbs and girdles was quite heavy. All the scars which have been preserved on the bones show that these muscles were strong and tendinous. The shoulder girdle seems to have been attached to the ribs by a very powerful levator scapulae profundus, which took origin from the enlarged ends of ribs 3–6 and was inserted on the dorsal margin of the scapula. The inferred condition of the dorsal muscles of the pelvic region has been mentioned in a previous paragraph. The musculature of this region seems to be advanced over that in *Diadectes* and in essentially the same condition as that in *Dimetrodon*.

Habits.—Williston has described *Labidosaurus* as a rather inactive form which inhabited the shores of lakes or the sea and gained its livelihood by digging for worms and larvae. Such conclusions are substantiated by the study of new material. The heavy musculature, the relatively inflexible axial skeleton, and the sprawling posture of the animal indicate that it was far from active. The anterior upper teeth overhang the lower jaw and are directed backward, as would be expected in a form which used its teeth in digging for food. Coupled with this is the strong vertical movement of the head, implied by the strength of the axial cervical muscles and the weakness of the occipital muscles. Williston suggested that the front feet also were used for digging. The limbs, however, are so short that they could not have reached the front of the long skull and could not have co-operated with the teeth in turning over soil and pebbles in search for food. They would have had to work independently. Also, it does not seem possible that they could have been turned forward enough to act with any efficiency. The heavy muscles of the limbs and girdles suggest an alternative view, that the feet were used to brace the animal while it was digging with its teeth.

Such a form as *Labidosaurus*—harmless, sluggish, and unintelligent—must have fallen easy prey to the active, carnivorous pelycosaurs of Clear Fork times.

CORALLOIDAL OPAL[1]

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AND
W. D. KELLER
University of Missouri

ABSTRACT

Coralloidal opal is an epigenetic opaline deposit found in lava tubes. The opal is precipitated by capillary waters on the tips of basalt spines and globules which causes the deposit to look like some forms of organic coral. Some of the opal gives a slight carbonate reaction. The source of material is found in the hydration of minerals in the surrounding basalt.

"Coralloidal opal" is a term used to describe an epigenetic formation, dominantly opal in composition, found in many of the lava tubes and caves in the Lava Beds National Monument in northern

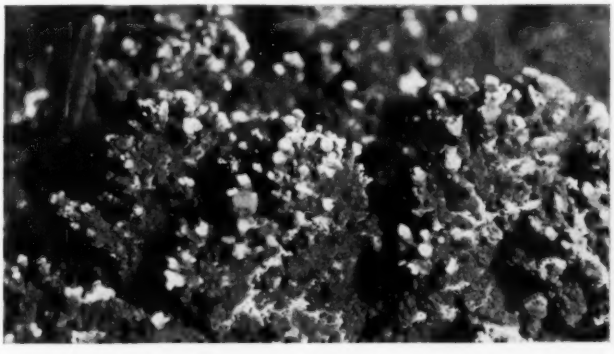

FIG. 1.—Coralloidal opal, from the Catacombs, Lava Beds National Monument. ×⅓. National Park Service Photo, by Crawford.

California (Fig. 1). In general appearance it resembles some of the varieties of organic coral, but it has no connection with them either as to mode of occurrence or to origin.

Only one description of a similar formation has been found in the

[1] Published by permission of the director of the National Park Service.

literature.[2] Some of the coralloidal opal from the Lava Beds National Monument resembles closely the formation described by Anderson. However, other different modes of occurrence were noted. The following paper describes the formation briefly and offers further suggestions as to its origin. Swartzlow studied the formation in the field during parts of the summers of 1934, 1935, and 1936. Keller carried on the microscopic investigations.

OCCURRENCE

The caves in which the coralloidal opal is found are simple lava tubes in the Warner basalt described by Powers (Fig. 2).[3] The ice

FIG. 2.—Typical lava tube or cave in the Lava Beds National Monument. National Park Service Photo, by Crawford.

caves, abundant in this region, some of which contain this growth, were recently described by Swartzlow.[4] The coralloidal opal, how-

[2] Charles A. Anderson, "Opal Stalactites and Stalagmites from a Lava Tube in Northern California," *Amer. Jour. Sci.*, Vol. XX (1930), pp. 22–26.

[3] H. A. Powers, "The Lavas of the Modoc Lava-Bed Quadrangle, California," *Amer. Mineralogist*, Vol. XVII (1932), pp. 253–94.

[4] Carl R. Swartzlow, "Ice Caves in Northern California," *Jour. Geol.*, Vol.. XLIII (1935), pp. 440–42.

ever, is not confined to the ice caves but is found also in caves that are comparatively dry. It occurs more or less abundantly in all the caves but is especially well developed in Labyrinth Cave and the Catacombs, where the specimens for photographing and microscopic study were obtained. These caves are situated in sections 28 and 33, T. 45 N., R. 4 E. (Mount Diablo Meridian). The two caves parallel each other for some distance and are over a mile in length.

The formation of coralloidal opal is probably taking place at the present time in caves where moisture appears on the interior, but in others the development is dormant. The most likely places are those where surfaces are harsh and splintery with many shards of basalt which act as nuclei for the deposition of mineral matter. The most extensive formations are found on the ceiling and walls, but the deposits have been observed in almost every conceivable position where there has been a sufficient concentration of moisture, even on the blocks of débris lying on the floor.

Rarely does any one mass show any relationship to another; it does not appear that the moisture forming one group could have dripped on another section of rock and continued the deposition of more silica. In most cases there is complete evaporation of the water at the point of egression from the ceiling, walls, or floor of the cave. In some instances, however, a true stalagmite has formed beneath a corresponding stalactite. This is true only where there is sufficient moisture to permit free dripping of the water. There is no apparent relationship between most of the coralloidal opal on the floor and that on the ceiling of the caves, even where there is actual dripping from the ceiling. Where the circulation of water is free and comparatively rapid, the stalactites and stalagmites are botryoidal in character, similar to those described by Anderson.[5]

Although in general appearance the larger deposits on the floor or walls of the caves are stalagmitic, the addition of new material to most of the deposits is from below and not from dripping waters from above. Moreover, those forms growing from the ceiling do not develop downward uniformly. In many cases they are branching, with the branches diverging from the main stem at almost any angle and in some cases recurving upward and pointing to the ceiling.

[5] *Op. cit.*, p. 23.

Where the surface of the cave is smooth and glassy the coralloidal opal is less likely to form. If the surface is so smooth that the moisture is a film over the surface, a uniformly thick deposit of opal is the result. Since the moisture film concentrates in the depressions, a thicker deposit of opal is frequently found in such places. In some caves small knobs of black basalt project beyond the opal and give the surface the appearance of white fabric. Such areas are known locally as lava lace and give rise to the name White Lace Cave, where this feature is rather well developed.

Where the caves are fissured the silica is often deposited in alinement with the cracks. Both sides of the fissure are coated with a white, banded, opaline deposit. Banding may represent seasonal deposition since there are definite wet and dry seasons in this area. Where no alinement along cracks is noted removal of the opal discloses porous basalt immediately behind the deposit. This indicates that coralloidal opal is likely to form in any place where moisture can reach the surface and is not dependent on secondary fissuring.

DESCRIPTION

There are three types of coralloidal opal. The first is lenticular in shape, resembling somewhat a grain of wheat. One end is sharply pointed and the other is slightly bulbous. The particles vary in length from $\frac{1}{2}$ to $1\frac{1}{2}$ cm. and from 2 to 8 mm. in diameter. This type is found in clusters with each individual attached to the cave wall by the sharp point. The nucleus for the deposition of opal is a small drop of basalt that had oozed out of a pore in the cave wall and is attached thereto by a small spine of basalt.

The second type is a botryoidal stalactite or stalagmite and in every way similar to those described by Anderson.[6] The stalactites average about 2 cm. in length and $\frac{1}{2}$ cm. in diameter. They are mostly hollow, and the outer surfaces are smooth and botryoidal. The accumulations of opal in this type started to form about lava stalactites (Fig. 3). The secondary opal deposit merely represents an extension of the syngenetic basalt stalactite. The opal stalagmites are slightly botryoidal hemispherical mounds.

The third type (Fig. 1) bears the closest resemblance to coral, and

[6] *Ibid.*, p. 24.

is usually found in patches about ½ square foot in area. It is dominantly dendritic in character and is found in all the caves and in all positions with respect to the interior of each cave. A number of stems protrude from the wall. These stems vary from a fraction of a millimeter to about 5 mm. in diameter and from a fraction of a millimeter to about 2 cm. in length. A number of branches radiate from the end of each stem, most of which are short and bulbous although

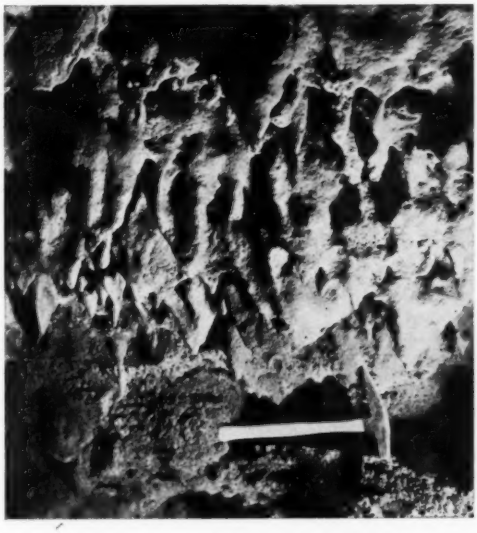

FIG. 3.—Typical lava stalactites found in Lava Beds National Monument. Hammer indicates proportions. National Park Service Photo, by Crawford.

some are long and slender. Many of the stems are covered with short acicular spines, giving the stems the appearance of being hairy.

The color of the coralloidal opal usually varies from white to dark gray. In a small number of cases it is light yellow to yellowish brown. White is the normal color of this variety of opal. The varying shades of gray are due to the amount of foreign matter (dust particles) that had adhered to the moist surfaces. The yellow and brown shades are caused by the presence of limonite, resulting from the oxidation and hydration of the ferrous iron from the pyroxenes in the basalt.

When examined petrographically, the branches of the growths are seen to be made up largely of overlapping layers of opal and chalcedony, opal predominating. In some instances a thin layer or coating of carbonate crystals may be included, but these are relatively scanty.

Some of the layers may be composed of very fine fibers of chalcedony lying with their long axes parallel to the length of the stalactites. In other cases layers may be composed of opal which shows no growth direction. Again, the succeeding bands may be opal which is stained or discolored differentially.

During development of the stalactites, fine dust particles settled on them and were embedded as further material was deposited on the growth. They consist of angular minerals, unweathered except for iron-oxide coatings, and came, no doubt, from the lava country rock. Plagioclase with composition about bytownite, hypersthene, dark amphibole, and reddish-brown iron oxide were identified in the "dust" particles. They may vary from 0.92 to 0.2 mm. in diameter, but the smaller sizes predominate. Iron oxide and feldspar particles are most abundant.

The index of refraction of the opal was found to vary approximately .01 above and below 1.420. A fragment of the whitest and purest (presumably most recently deposited) opaline growth was selected for closest study. Even this material varied in index of refraction from 1.410 to 1.420, although a large proportion of it showed about 1.413. These values lie toward the lower end of the range of indices given for opal in the handbooks[7,8] of optical constants for minerals. According to Winchell, the index of opal varies with its tenor of water. A half-gram portion of the foregoing sample was ignited and its loss in weight found to be 11.53 per cent. A slightly higher water content is to be expected if the sample is pure, uniformly low-index opal, but since the average index of this one is higher than 1.413 and since it contains dust impurities of practically water-free minerals, the low ignition loss is consistent with the sample as a

[7] E. S. Larsen and Harry Berman, "The Microscopic Determination of the Nonopaque Minerals," *U.S. Geol. Surv. Bull. 848* (1934). *N* varies from 1.406 to 1.46.

[8] A. N. Winchell, *Elements of Optical Mineralogy*, Pt. II. (New York: John Wiley & Sons, 1933). *N* varies from 1.409 to 1.46.

whole. Variations in opacity and amounts of impurities, as well as index of refraction, aid in producing visible textural figures in the opal.

The fibrous branching "core" shown in the photomicrograph (Fig. 4) is relatively free from dust impurities except in the basal portion. Sections cut parallel to the base are roughly circular in outline and show concentric growth. Although the presumption might be that the chalcedony represents a later crystallization of the opaline silica,

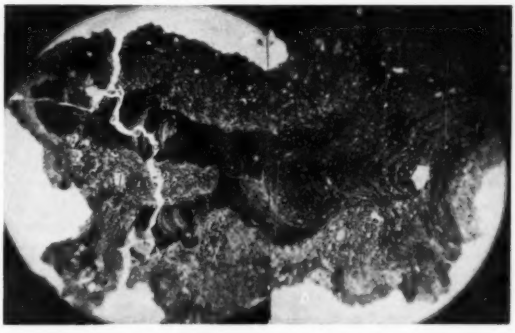

FIG. 4.—Photomicrograph ×6.5. The banded structure is opal. The small specks are dust particles which have adhered to the moist surfaces.

the cause for the change in structure between core and exterior is not readily apparent from a thin-section study.

COMPOSITION AND ORIGIN

Coralloidal opal is dominantly opal in composition. Some of the specimens gave weak carbonate reactions, but their number is small compared to those that showed no reaction whatever.

The cave described by Anderson was visited by Swartzlow, and the deposits studied and compared to those in the Lava Beds National Monument. In all cases where the Lava Beds opal was similar in appearance to Anderson's specimens, there can be little doubt that the origin is as Anderson suggests.[9] The additional explanation for those forms not truly stalactitic or stalagmitic (those projecting from the sides of the caves or being built up from the floor) is to be

[9] *Ibid.*, p. 25.

found in capillary action or the slow seepage of waters through the porous basalt.

The deposition is caused by evaporation. The source of the silica is not definitely known. It is suggested that it may result from the hydration of minerals composing the basalt. The breakdown of these minerals may have been partially accomplished by hot, moist gases at the time of the lava flows, and later released by the percolation of ground waters. There are no hot springs in the immediate area to indicate that thermal activity has released the silica.

The presence of a carbonate in some of the specimens may be due to the formation of a bicarbonate by percolating ground waters and subsequent deposition as the carbonate at the point of evaporation. The feldspars and pyroxenes in the basalt undoubtedly supplied all the minerals present. In numerous places disintegrated basalt was found, showing that the constituents may have been obtained from nearby sources. The fact that much of the coralloidal opal is apparently growing on unaltered basalt may be explained by the percolating waters becoming saturated with silica or carbonate or both before appearing at the surface. Thus they would be unable to break down the basalt at the point of egression.

REVIEWS

"Reports on the Geology of Cameron and Vermilion Parishes." By HENRY V. HOWE, RICHARD J. RUSSELL, JAMES H. MCGUIRT, BEN C. CRAFT, and MORTON B. STEPHENSON. In the *Louisiana Department of Conservation Geological Bull. 6.* New Orleans: La. Dept. of Conservation Geol. Surv., 1935. Pp. 242; figs. 23; pls. 10; Bibliography.

The reports comprise: (1) Howe, Russell, and McGuirt, "Physiography of Coastal Southwest Louisiana," mainly a discussion of the coastal marshes and beaches (locally termed "cheniers" from the oaks on them), and the past and a postulated very recent subsidence of Vermilion and Cameron parishes; (2) Howe and McGuirt, "Salt Domes of Cameron and Vermilion parishes," Old Hackberry, East Hackberry, Black Bayou, Cameron Meadows, and Calcasieu Lake domes, Sweet Lake oilfield, Gueydan dome; (3) McGuirt, "Salt Dome Prospects"; (4) Craft, "Mineral Development," drilling and production methods, shells, salt, oil, and gas; (5) Stephenson, "Some Microfossils of the Potamides Matsoni Zone of Louisiana"; (6) McGuirt, "A Partial List of Maps Dealing with Cameron and Vermilion parishes"; (7) Bibliography of 103 references with brief annotation of each reference.

This is another one of the valuable parish (county) reports by Howe and his associates. As in the preceding two reports, on Iberia Parish and on St. Martins and Lafayette parishes, much information has been compiled from the files of the oil companies and made publicly available, together with data from the files of the Department of Conservation, and with results of work by the staff of the Louisiana Geological Survey.

Drastic disagreement with much of the physiographic argument in regard to modern subsidence must be registered by the reviewer. In spite of such expressions as "certainly" (p. 31, l. 3) and "undoubtedly" (p. 33, l. 17), the example of the known(!) subsidence of the New Jersey coast at the rate of two feet per century (p. 43), subsidence an absolutely essential condition for the development of Grand Lake (p. 57, l. 10), and the dogmatic statement that standing dead cypress trees indicate subsidence, the reviewer believes that beach ridges themselves give reasonably reliable evidence of considerable stability of the southwest Louisiana shore line during very recent time. Little attention seems to have been paid to the work of D. W. Johnson and others on the alleged subsidence of the At-

lantic Coast and on criteria for recognizing shore-line movements. Little attention is paid to the elevation of the beach ridges as evidence for or against subsidence. No attempt is made to reconcile the postulated subsidence with the fact that the elevation of the beach ridges seems to show no relation to age. No consideration is given to alternative explanations of the facts used as evidence for subsidence. For example, it would seem that in discussing the significance of the dead cypress trees in the Lake Arthur district, some consideration should be given to the effects of the large intercoastal canal which extends from Vermilion Bay to Calcasieu Lake.

DONALD C. BARTON

"The Eruption of Mt. Pelée 1929–1932," by FRANK A. PERRET, in *Carnegie Institution of Washington Publication 458*. Washington: Carnegie Institution, 1935. Pp. 126; figs. 71; frontispiece; chart.

This outstanding contribution to volcanology consists of two sections, narrative and analytical. In the narrative Dr. Perret gives not only a vivid account of the three-year period of activity but also the methods by which eruptions are studied and predicted. In the field he uses a seismoscope and microphone, with which he studies every tremor and the pitch of resulting vibrations. One cannot deny, he says, the trigger effect of the lunar-solar maximums, and he watches the astronomic calendar with care. Temperature changes and chemical variations in fumaroles are noted, but above all he draws on the past record of the individual volcano in making predictions. Perret asserts that it is still impossible to predict the date of initiation of an eruptive period; but, once started, the progress of an eruption can be foretold with certainty.

The 1929–32 eruptive area was confined to the limits of the 1902 eruption, and the lavas of each were chemically identical. The relation between these two historic eruptions would have been more clear with the aid of a map. From his study of the geologic history of Mont Pelée Dr. Perret observed that the violence of the recent eruptions was much less than that which characterized its youth.

Two distinct phases characterize Peléan eruptions: the *nuées ardentes* charged with auto-explosive gases, and dome-building of gas-free incandescent lava. The initiation of a *nuée ardente* is powerfully explosive, as shown by Perret's close observation of several hundred *nuées*. He claims that explosions of the lava per se produce *nuées ardentes* as the result of rapid vesiculation due to superheat in a gas-charged lava. He even suggests the possibility that the fine ash is condensed lava vapor emitted from the magma. The true nature of the *nuée* is well illustrated by its

manifold reactivitation due to mechanical shock. These recurrent outbursts show the explosive power of the gas-charged particles and are best revealed where barriers are met. The speed of a *nuée ardente* varies in different parts of its course, further indicating the reactivation. The fastest recorded speed of a recent *nuée*, in 1929, was 33 meters per second, or nearly 70 miles per hour. This same cloud reached an altitude of 6,000 meters.

The study of gases in a *nuée ardente* has not progressed far, owing to lack of sampling equipment, though the *nuée* probably offers the best opportunity for the study of primary volcanic gases. In one of these clouds, in which Perret lived for a half-hour, he observed no trace of H_2S, SO_2, or HCl and suggests CO as the cause of the resulting anemic condition he experienced. Walking into the edge of another *nuée* he noted the presence of alkali chlorides. In others, steam, H, N, HCl, and heavy hydrocarbons are present. Dr. Perret assigns a much higher temperature for the acid lavas of Peléan volcanoes than is commonly assumed, his observations indicating an internal crater temperature of at least 1,200° C.

Moving *nuées ardentes* were observed to be soundless except where differences in electrical potential were great enough to produce discharges. The absence of sound is attributed to the cushioning effect of compressed gases. The buoyancy of the gases, which normally would cause the cloud to rise, is offset by the weight of ash which results in a rush of the cloud laterally from the crater. A descending cloud actually furrows a valley instead of leaving a deposit.

Several modifications of the *nuée ardente* are described, the most important being the steamy outburst resulting from a heavy downpour of rain on the hot dome. Another is a gas-free flow of block lava accompanied by coeval ash, rendering the flow as silent as the ordinary *nuée*. The electrical manifestations in the *nuées* of highest intensity are due to friction between ash particles and the volcanic steam and other gases producing the differences in potential. These give rise to terrifying discharges and flashes. Perret ascribes the "self-cohesive" quality of a *nuée*, where the closeness of its contours is ma˙ntained at a distance from its source, to the attraction between oppositely charged vapor and ash, even though the air-gap is too great to permit visible or audible discharge. "Flashing arcs," "forward-springing jets," "in-draught," and "return wind" are minor phenomena which have not escaped Perret's observation. He considers the *nuée ardente* the most important phase of volcanism and urges the construction and equipping of a field station on Morne Lénard for its further study.

Dr. Perret's observations have shown that dome-building is a late stage in the eruption of an acidic volcano and that the formation of a dome

marks the final evolutionary step of a volcano of this type. These observations are valuable in volcanological diagnosis and prediction, and also throw light on the rise of lava in the conduit, the relationship between domes and spines, and the value of dome resonance as an index of dome development. Dome-building is always vertically upward, as must be the case in a moving liquid magma where the way-maker is the vast quantity of gas in solution.

This beautifully illustrated book is a remarkable memoir of the detailed phenomena of Pelée's recent activity and, in addition, gives the student of volcanology many new and noteworthy suggestions for the understanding and solution of the volcano problem.

G FREDERICK SHEPHERD

The Geological Map: An Elementary Text Book for Students of Geography and Geology. By KENNETH W. EARLE. London: Methuen & Co., Ltd., 1936. Pp. 96; figs. 41. Price 3*s.* 6*d.*

The author's expressed purpose has been to produce a book which, by the use of only the most simple language and by the suppression of all superfluous detail, shall be intelligible to students of geography and geology alike. A chapter is devoted to an elementary discussion of each of the following geologic features together with their recognition on maps: outcrops, unconformities, folds, faults, inliers and outliers, and igneous and metamorphic rocks. A chapter on geologic map reading and section drawing and another of descriptions of a few representative geologic maps of districts in the British Isles complete the volume.

The author has accomplished his objective, but to the simplification are probably to be charged an unfortunate number of faulty statements. It is hardly felicitous to state (p. 4) that river alluvium and raised beaches "will show no true stratification like the deposits laid down under the sea" and "will contain no indigenous fossils"; that the direction of strike is always a straight line (pp. 11 and 12); that discordance of strike is a certain test of an unconformity (p. 25); or that "a fault is a dislocation of the strata forming the crust of the earth, due to tension consequent on folding, earthquakes, or isostatic readjustments" (p. 39). At the beginning of chapter vi an inlier is defined as an area of older rocks entirely surrounded by newer, and an outlier as an area of newer rocks entirely surrounded by older. But the student who reads at the end of the chapter that "klippen are detached outliers . . . ." and that "windows, on the other hand, are inliers . . . ." is likely to be considerably perplexed if he tries to diagram the formation of a klippe or a window.

R. T. C.